Higgs pair production at the LHC at NLO

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Based on arxiv:1401.7340

Fermilab Seminar

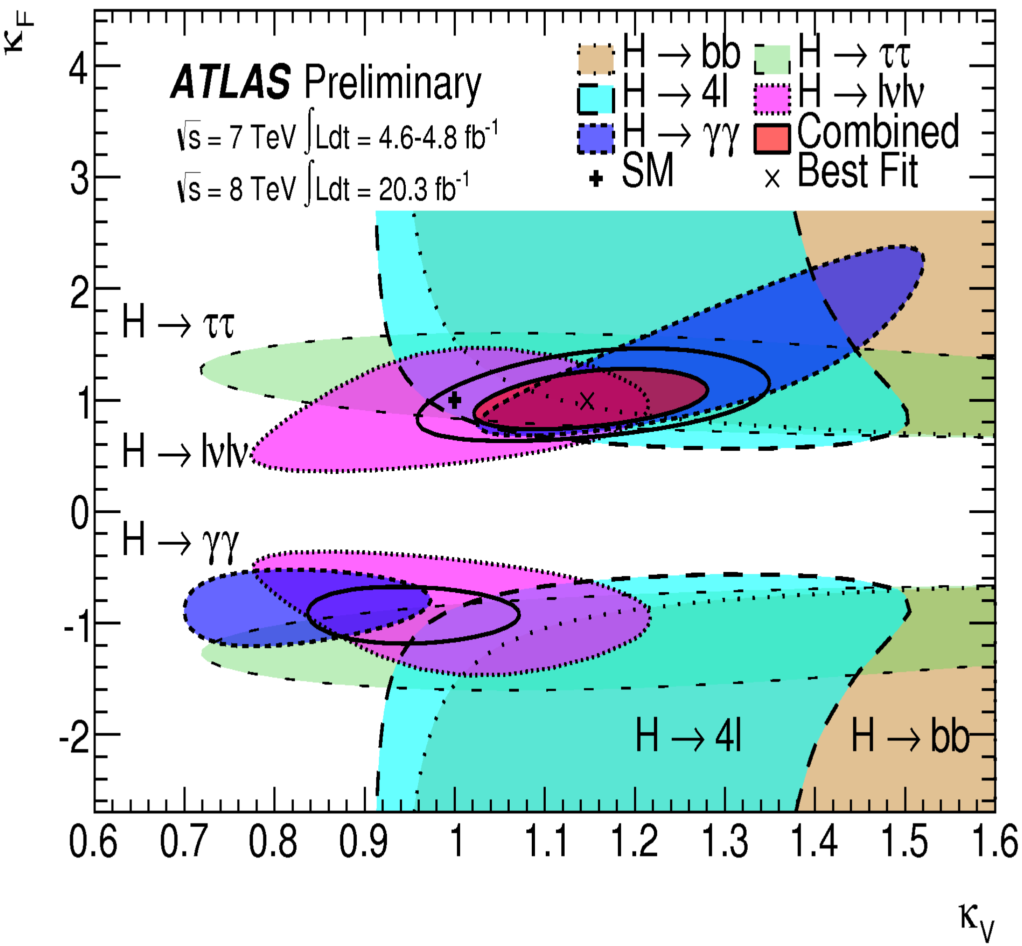
9/5/14

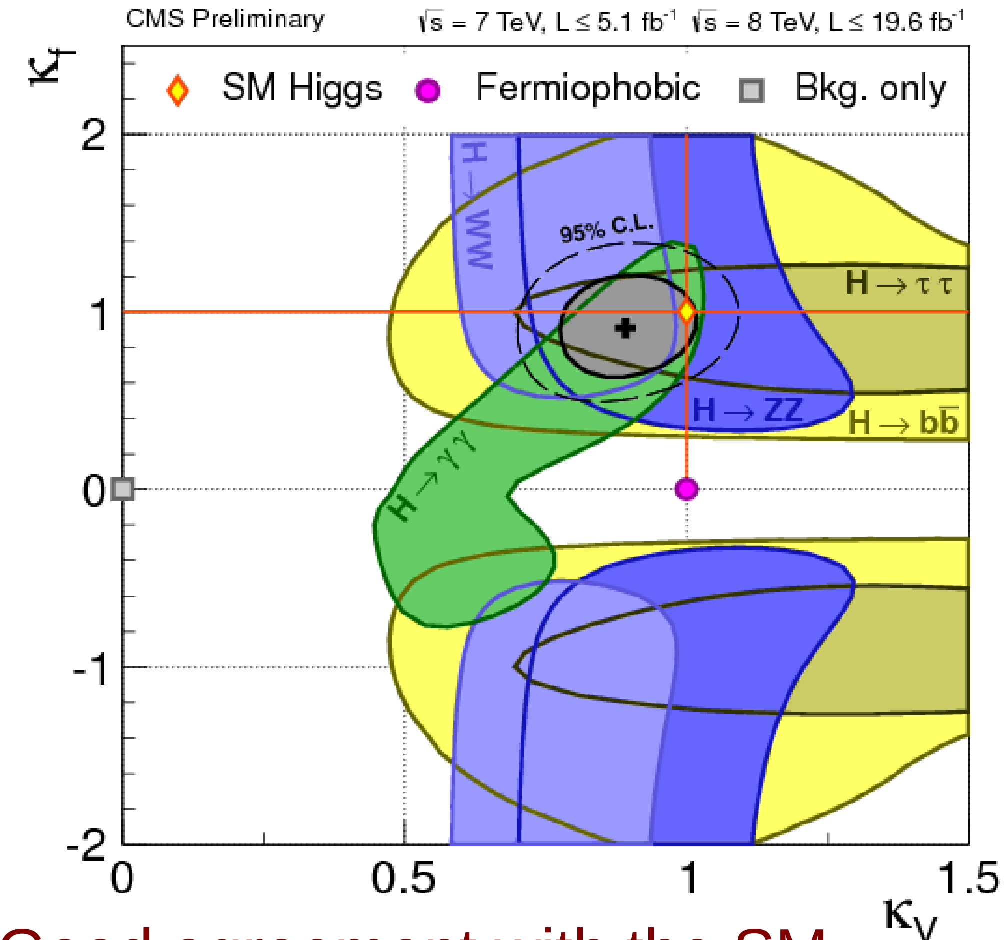
Outline

- Motivation of HH study
- HH in gluon fusion
- aMC@NLO Results
- BSM in HH
- Outlook

Motivation

- Higgs discovery → SM Higgs?
- Spin, parity measurements
- Higgs couplings measurements:
  Couplings to fermions and gauge bosons





Good agreement with the SM

Motivation

- ***Higgs self couplings***
- Higgs potential:

$$V(H) = \frac{1}{2} M_H^2 H^2 + \lambda_{HHH} v H^3 + \frac{1}{4} \lambda_{HHHH} H^4$$

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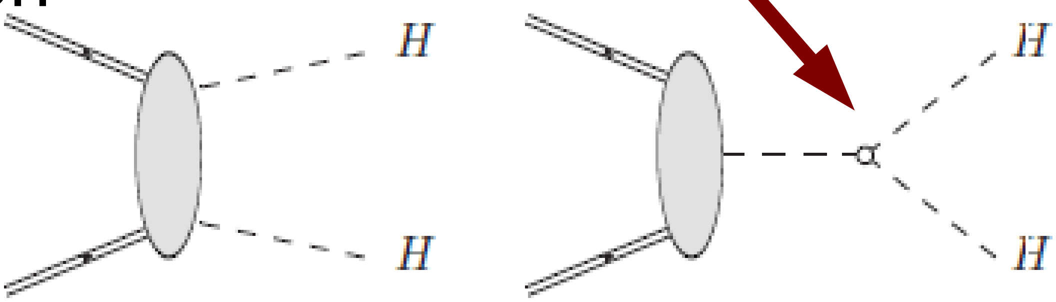
Higgs pair production



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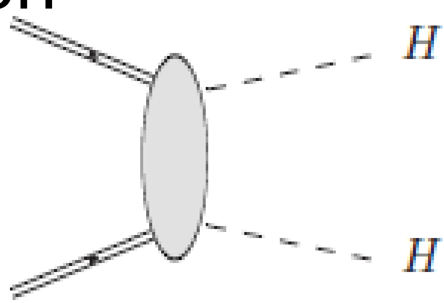

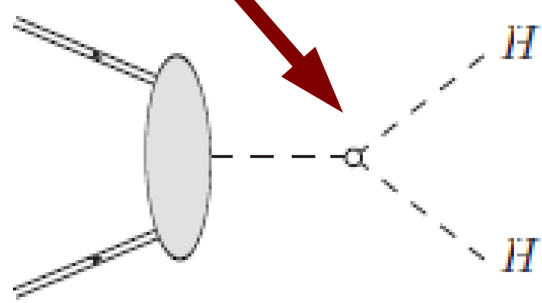

Triple Higgs production

4fb at 100TeV

more later...

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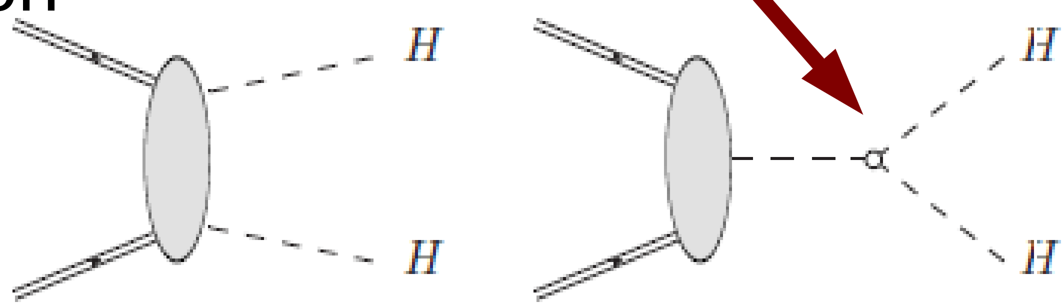

Value of the couplings fixed in the SM

$$\boxed{\lambda_{HHH}=\lambda_{HHHH}=\frac{M_H^2}{2v^2}}$$

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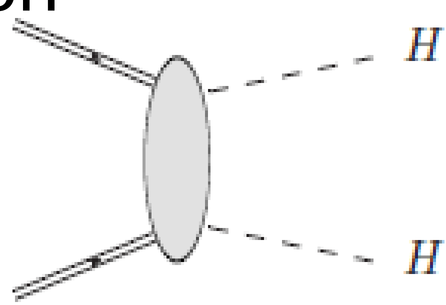
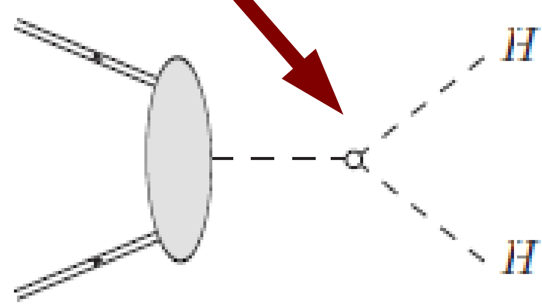
Higgs pair production





Triple Higgs production
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more later...

Value of the couplings fixed in the SM

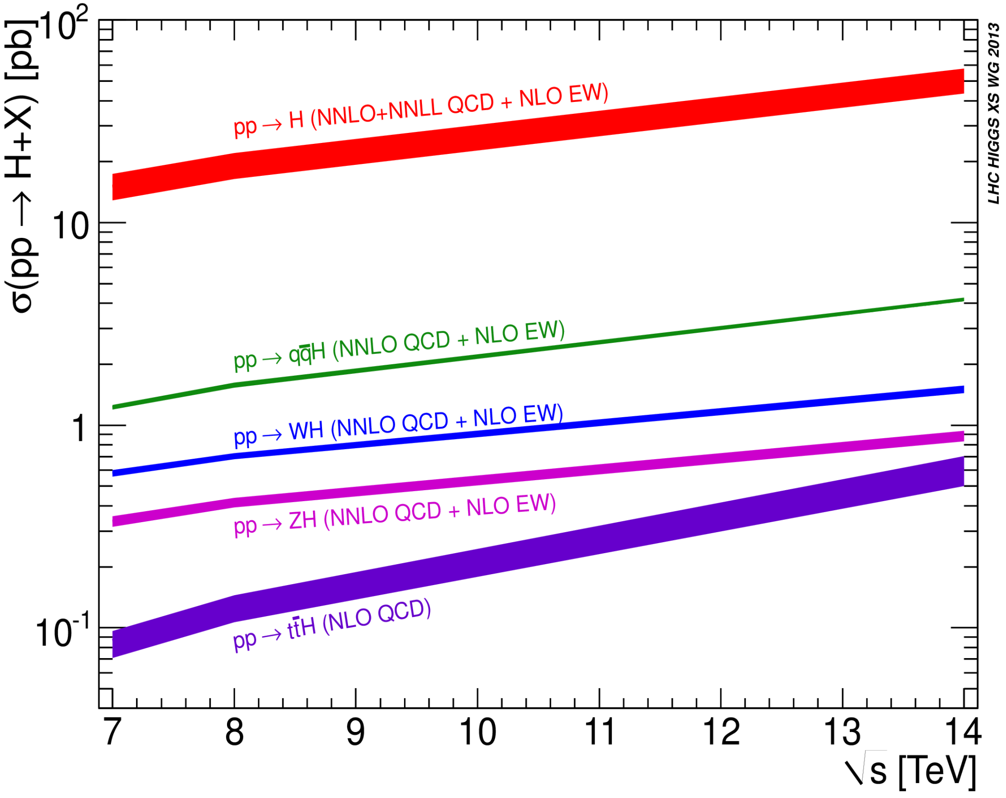
$$\boxed{\lambda_{HHH}=\lambda_{HHHH}=\frac{M_H^2}{2v^2}}$$

SM and similarly in extensions: e.g. THDM

Higgs Pair Production channels

In single Higgs production:
Higgs coupling to heavy quarks and gauge bosons

- Gluon-gluon fusion
- Vector boson fusion
- Vector boson associated production
- Top pair associated production

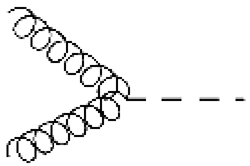


Single Higgs

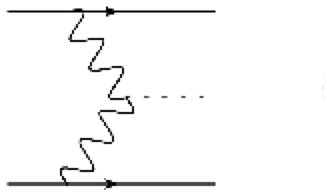
LHC Higgs Cross Sections Working Group

Higgs Pair Production channels

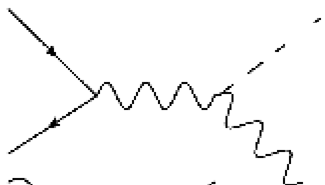
gg



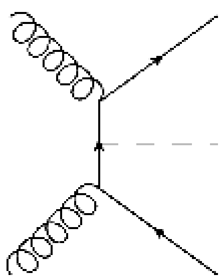
VBF



VH



ttH



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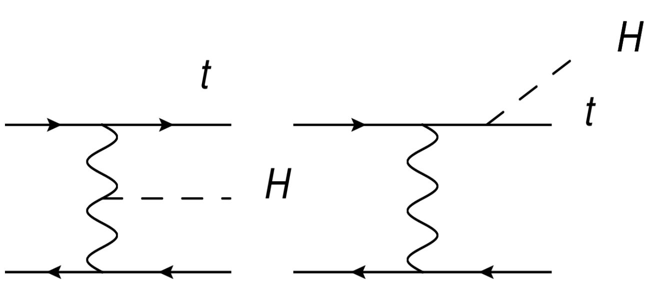

Higgs Pair Production channels

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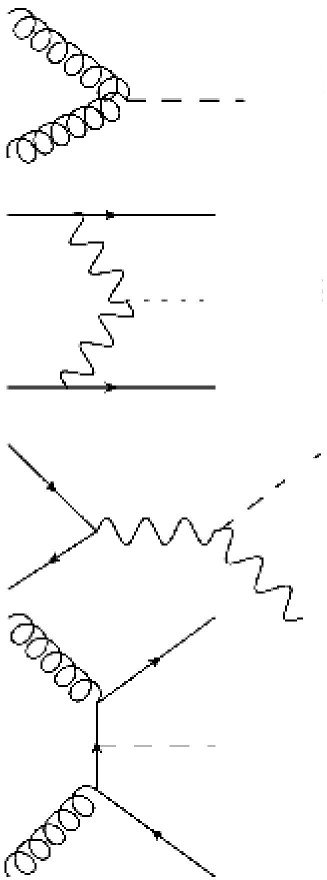
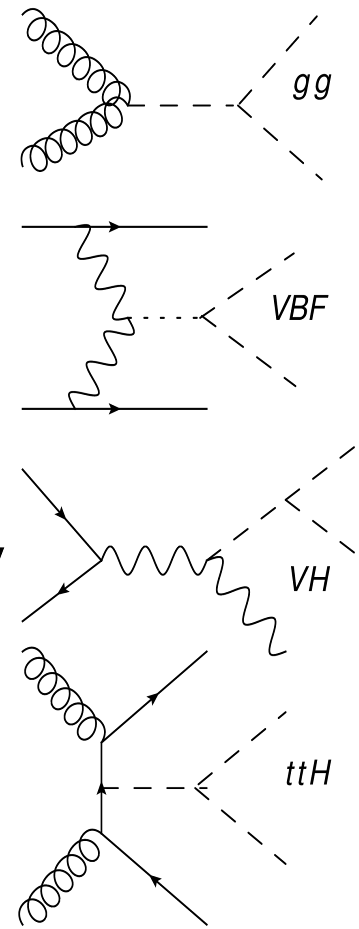


Schematically



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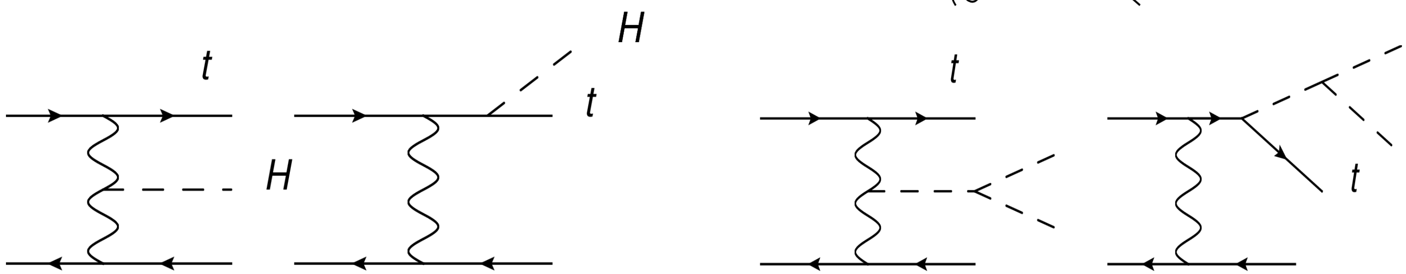

Higgs Pair Production channels

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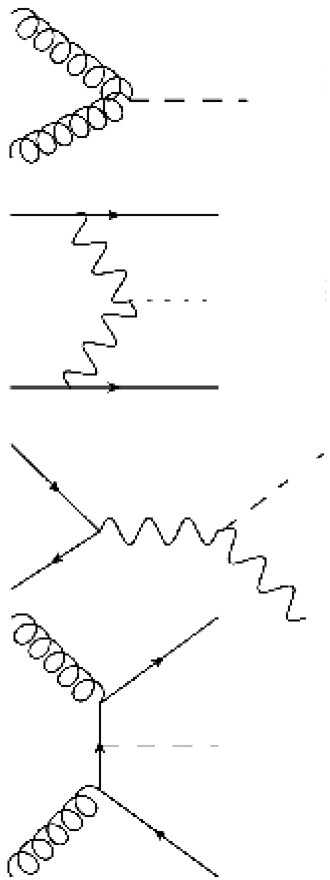
ttH



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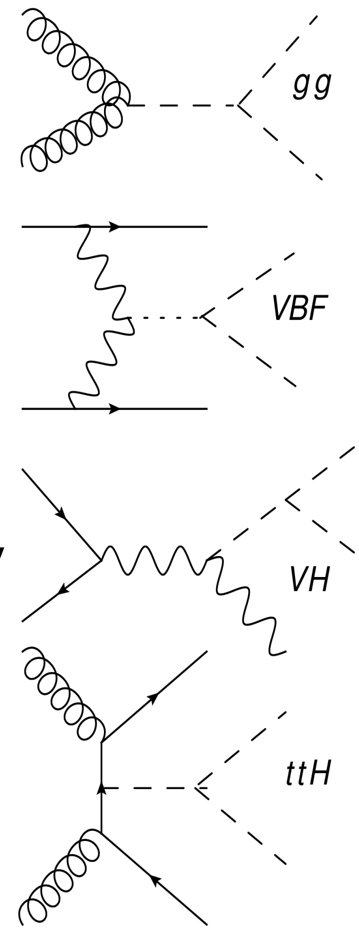

Heavy quarks

Vector bosons

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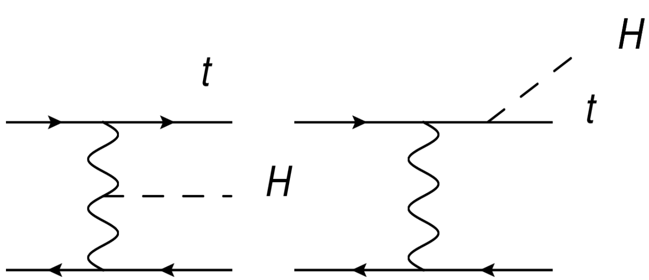
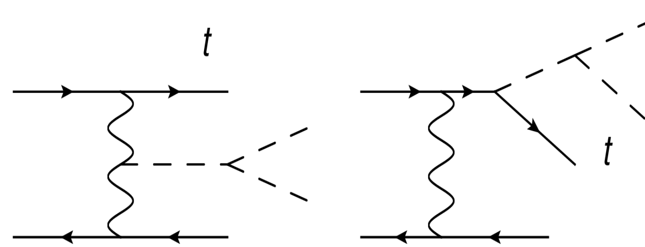
tH





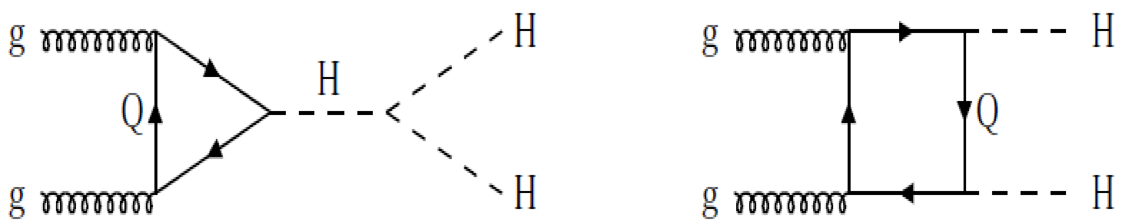
Heavy quarks + vector bosons

Questions about HH?

- How does the hierarchy of the channels change for HH at 14TeV? Is gluon fusion the dominant one?
- How does the cross section change with the centre of mass energy?
- How do the results depend on the value of the trilinear Higgs coupling?
- Can we accurately obtain the results? Do we have NLO predictions?
- Do we have an efficient fully differential Monte Carlo implementation of the process?
- What has been done at a more phenomenological level including decays?

Higgs pair production in gluon gluon fusion

- Only channel which starts with a loop at LO



- Coupling to heavy quarks, sensitive to extra heavy quarks (arxiv:1009.4670, 1206.6663)
- Interesting to study the interplay between the diagrams

Higgs pair production in gluon-gluon fusion

- What do we know at LO?

  Glover and van der Bij: NPB 309(1988)282

  Plehn, Spira, Zerwas: Nucl.Phys. B479 (1996) 46-64

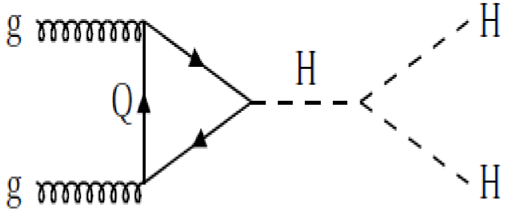
- Compact expresions for the loop amplitudes:

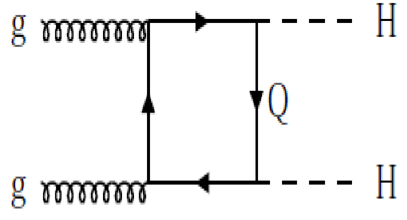
$$\boxed{\frac{d\hat{\sigma}(gg \to HH)}{d\hat{t}} = \frac{G_F^2 \alpha_s^2}{256(2\pi)^3}\left[|C_\triangle F_\triangle + C_\Box F_\Box|^2 + |C_\Box G_\Box|^2\right]}$$

$$C_\triangle = \lambda_{HHH}\,\frac{M_Z^2}{\hat{s} - M_H^2}$$

$$C_\Box = 1$$

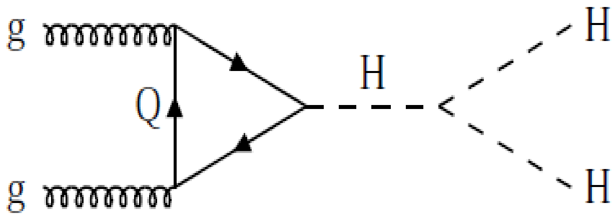
Form factors
(loops)

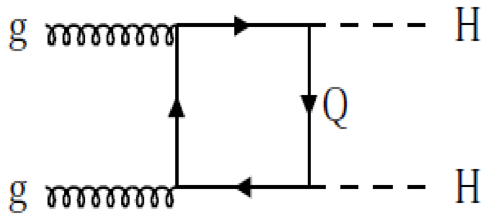




Form factors in gluon-gluon fusion

- What do these form factors mean?





$S_z=0$ F_Δ

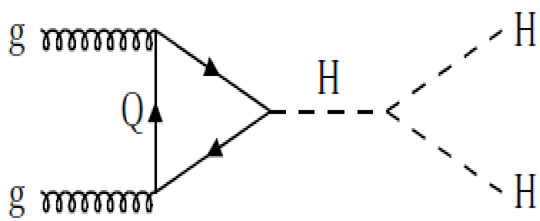
$S_z=0$ or $S_z=2$

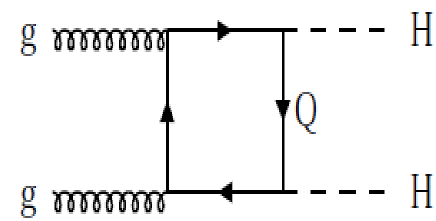
$F_\Box$ and $G_\Box$

- Form factors functions of kinematic variables and scalar integrals
- Main contribution comes from top quark loop (b-quark contribution ~0.1%)

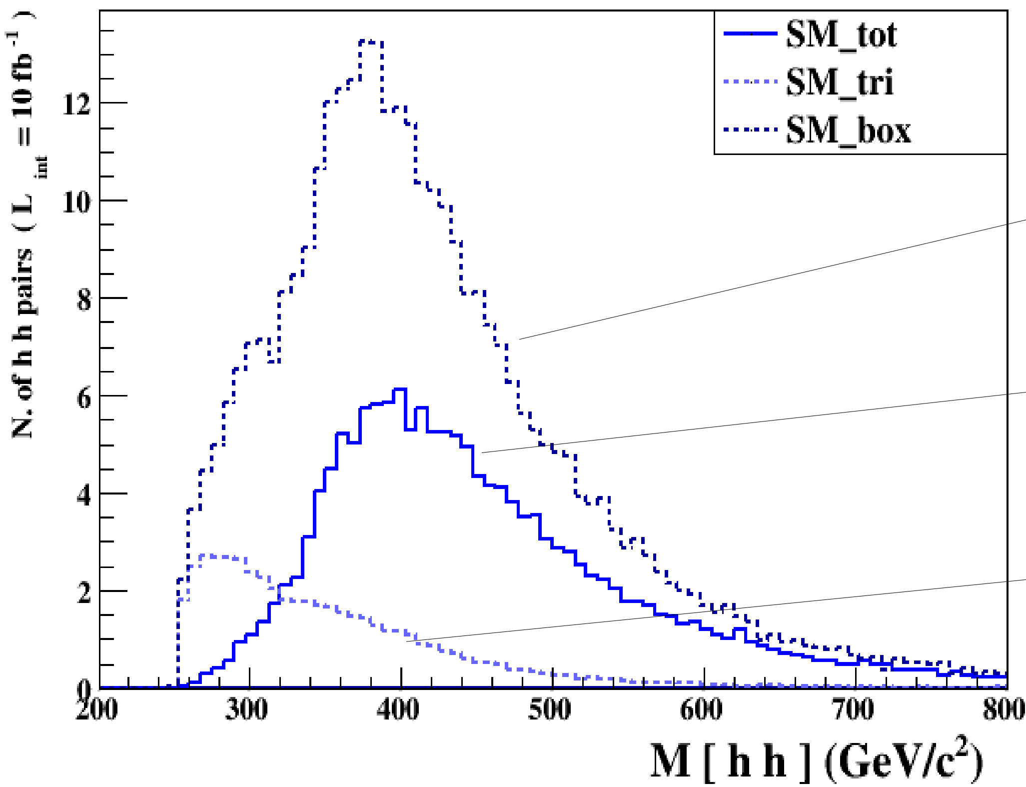
Decomposing into diagrams...

- At LO...





How much does each diagram contribute?



Box

Total

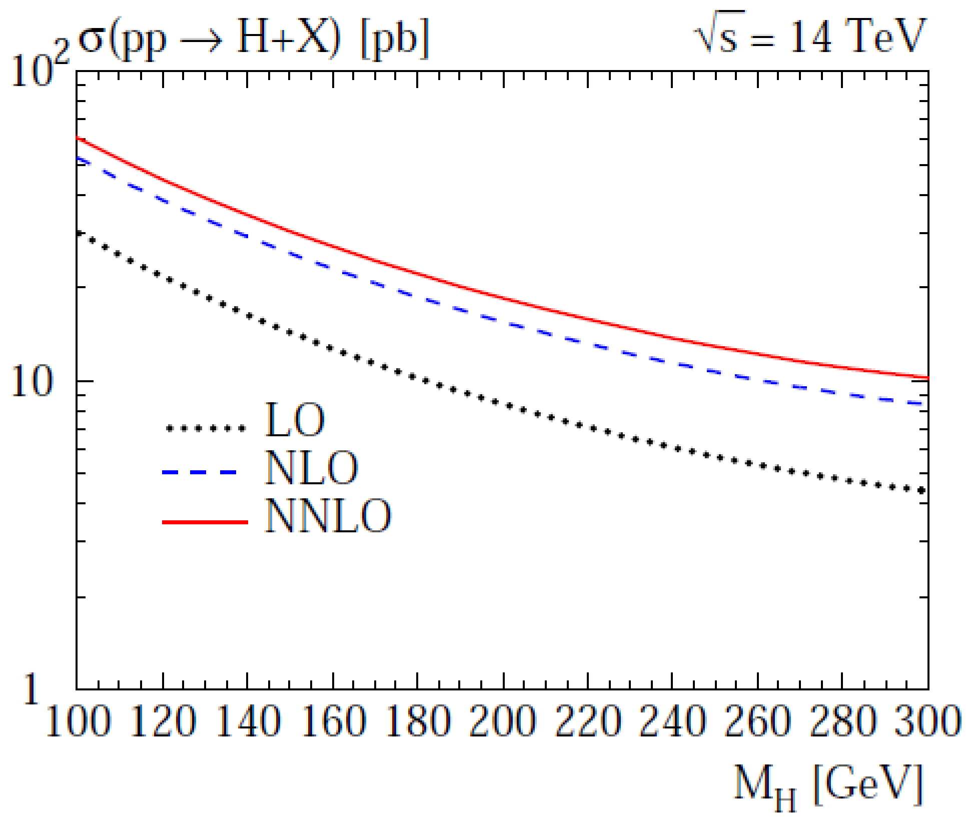
Triangle

Significant cancellation between the two diagrams

Negative interference for the SM

High energies: Box dominates
Triangle decouples

Taking gluon-gluon fusion a step further



Harlander, Kilgore, hep-ph/0201206

Again starting from single Higgs input:

- Large k-factors
- LO is not enough

Need for NLO predictions

HH in gluon-gluon fusion

Loop induced process

- Difficulty in higher order calculations
- MC automation

HH in gluon-gluon fusion

Loop induced process $\Rightarrow$

- Difficulty in higher order calculations
- MC automation

Single Higgs solution:

Use a low energy theory, taking the $m_t >> m_H$ limit:

Effective Lagrangian

$$\mathcal{L}_{\rm eff} = \frac{1}{4}\frac{\alpha_s}{3\pi} G^a_{\mu\nu} G^{a\,\mu\nu} \log(1 + h/v)$$

$$\mathcal{L} \supset +\frac{1}{4}\frac{\alpha_s}{3\pi v} G^a_{\mu\nu} G^{a\,\mu\nu} h - \frac{1}{4}\frac{\alpha_s}{6\pi v^2} G^a_{\mu\nu} G^{a\,\mu\nu} h^2 .$$

HH in gluon-gluon fusion

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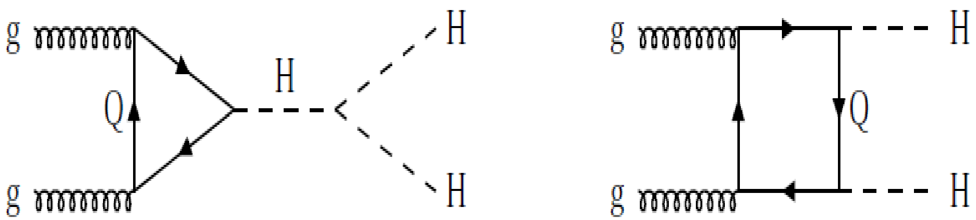

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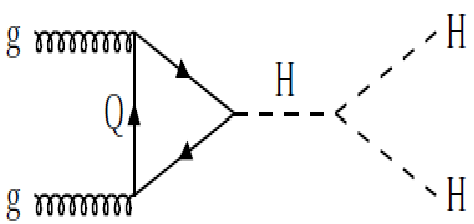
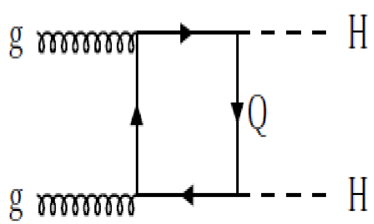
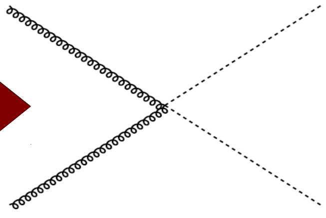
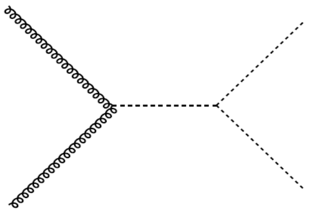


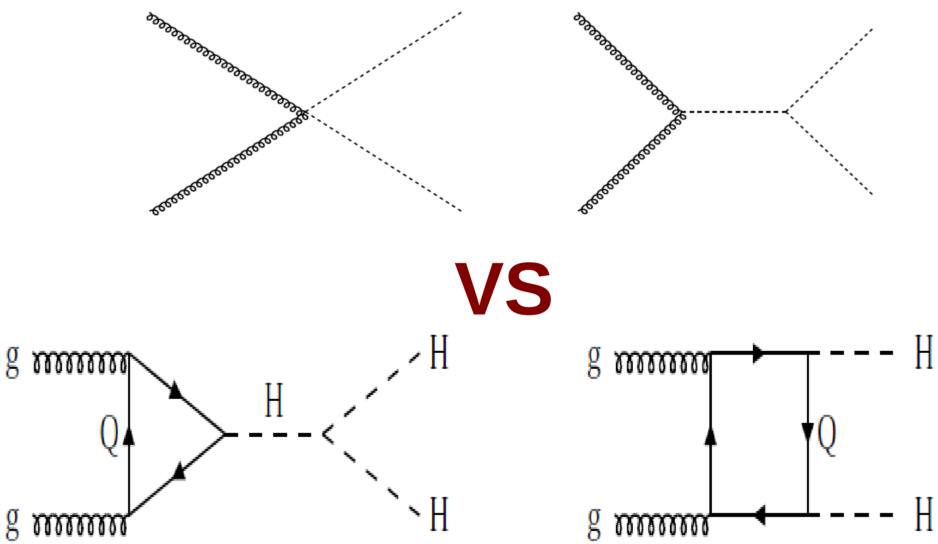


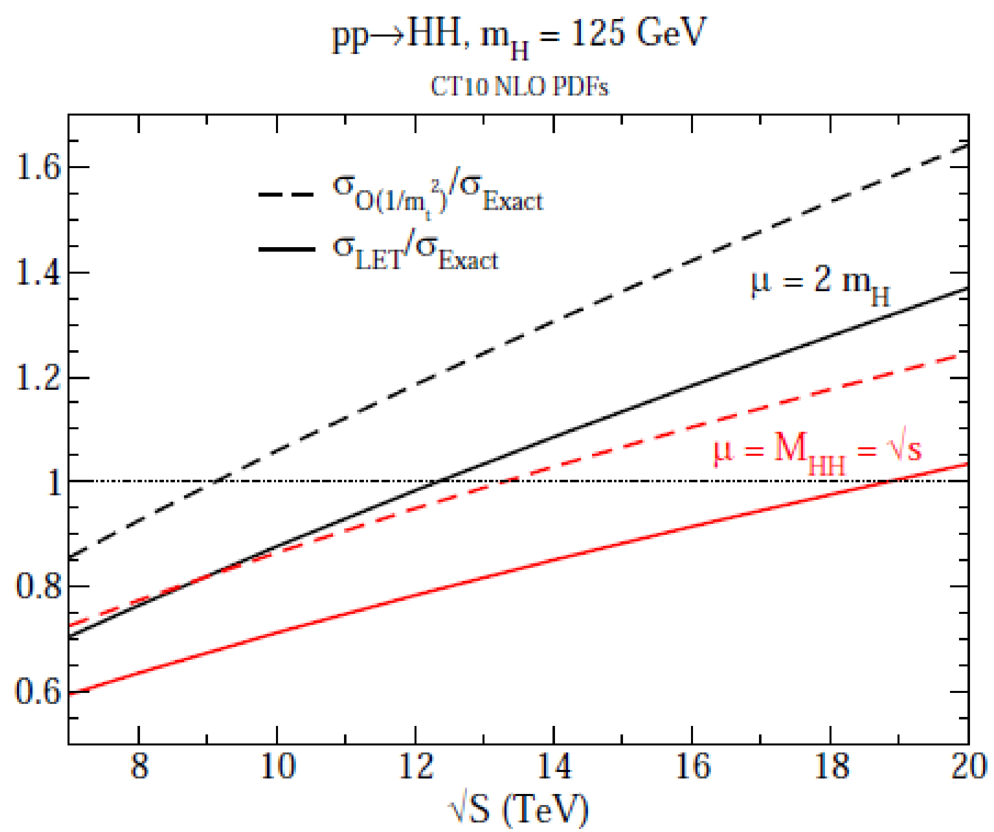




Does the effective theory work?

- LET known to work quite well for single Higgs
- Is this the case for HH?





Dawson, Furlan, Lewis 1206.6663

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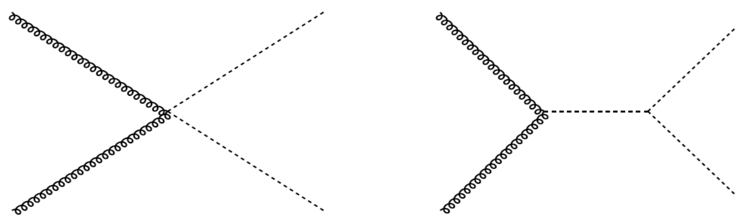
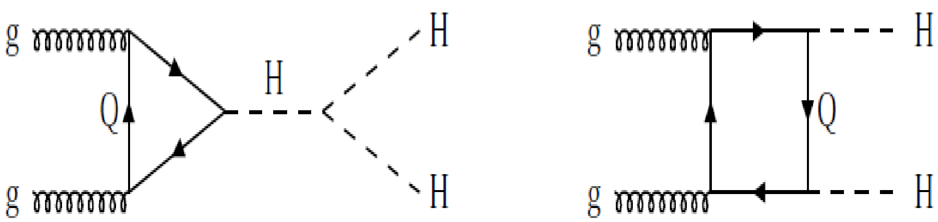
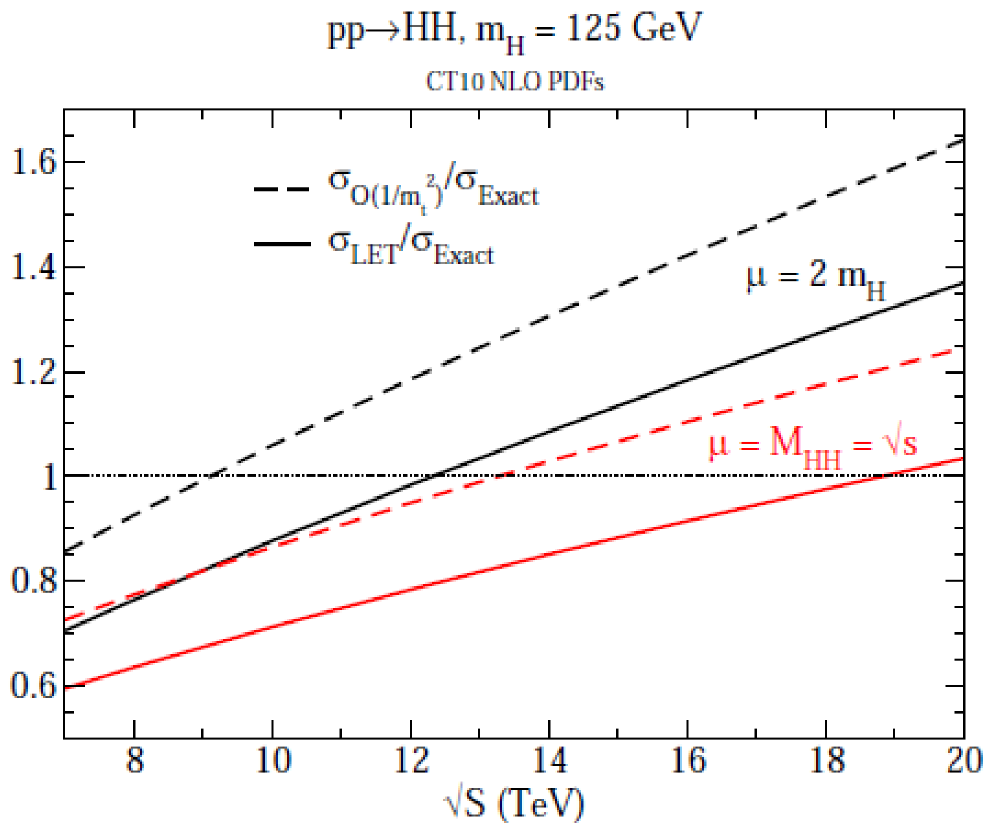


VS



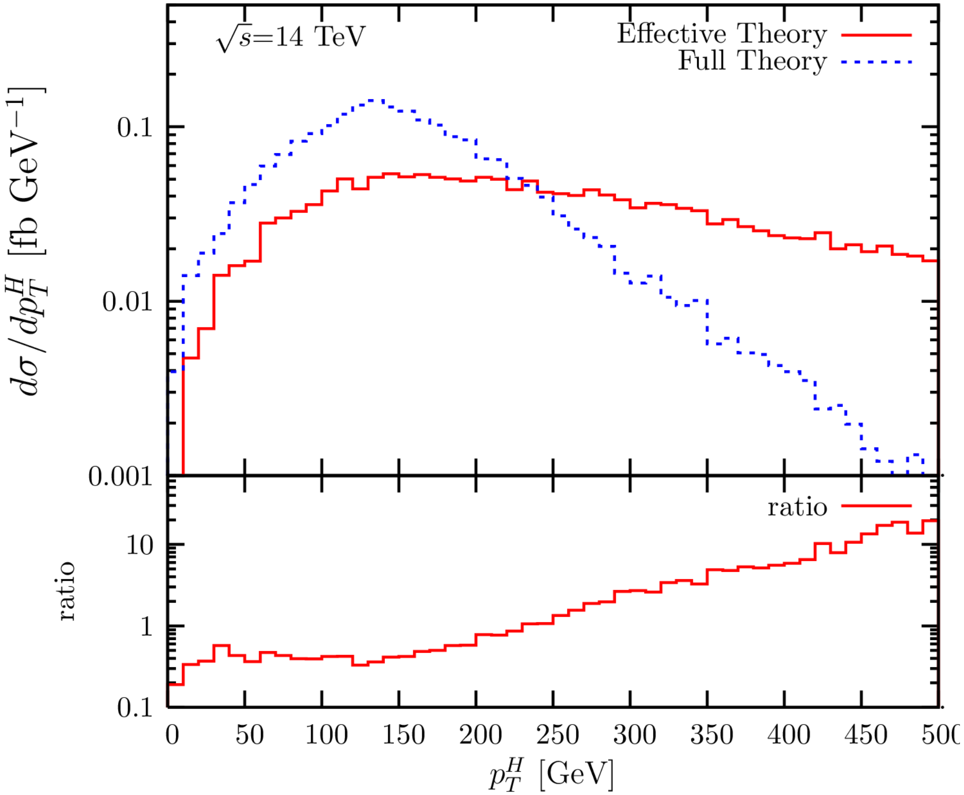


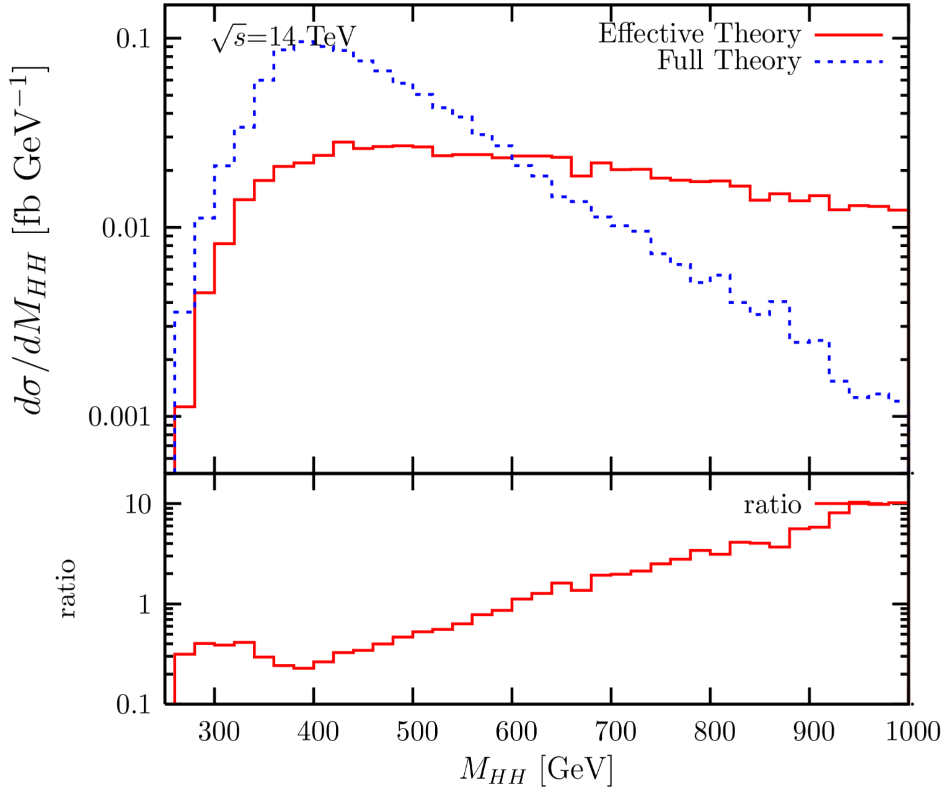
Dawson, Furlan, Lewis 1206.6663

10-20% difference in the total cross section at 14 TeV(depending on the scale choice)

Looking closely...

- Differential distributions p_T and m_{HH}





Using MadGraph5 implementation of LET and MadLoop

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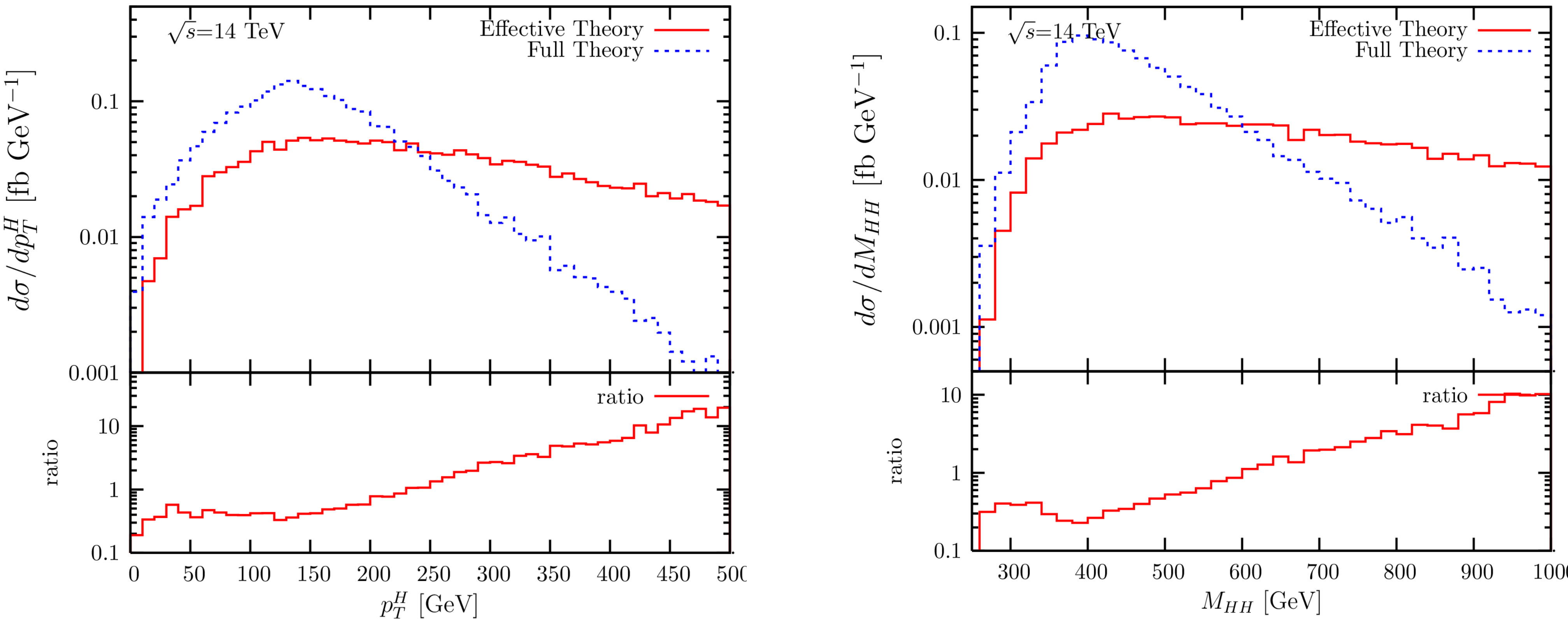
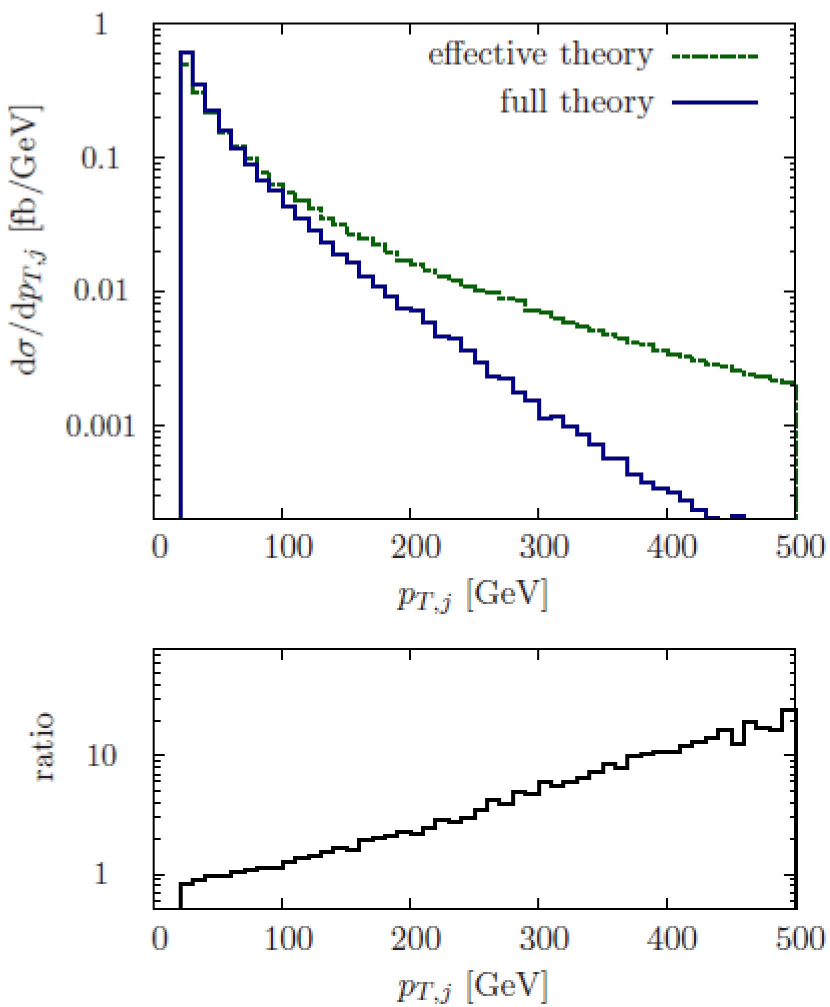


Using MadGraph5 implementation of LET and MadLoop

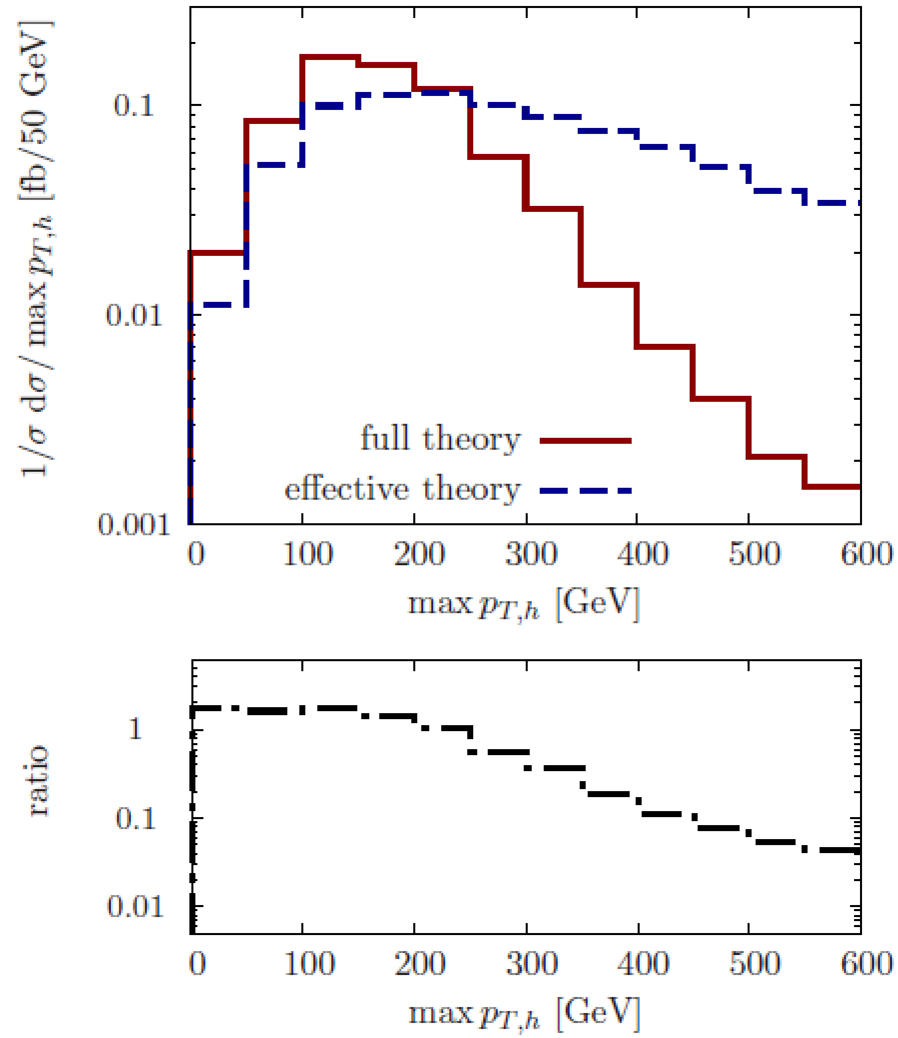
Low energy theory fails to reproduce kinematic distributions

Higgs pair plus 1,2 jets

How good or bad is the LET for HH+jets?



Dolan et al. 1206.5001



Dolan et al. 1310.1084

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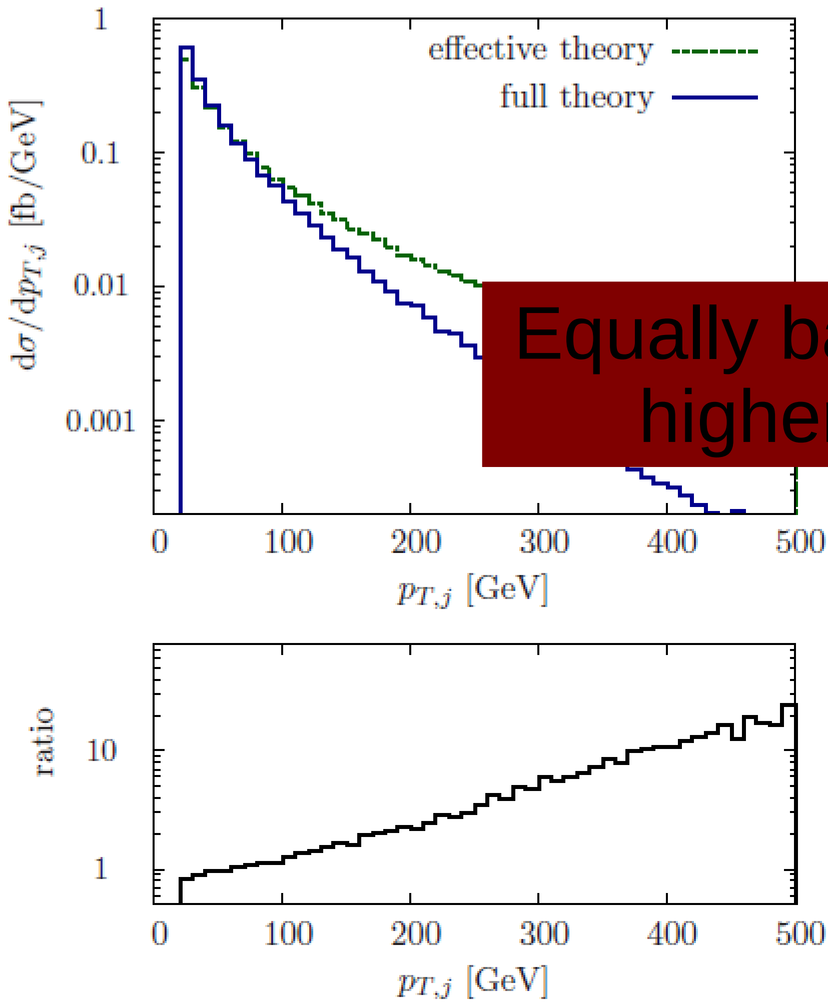

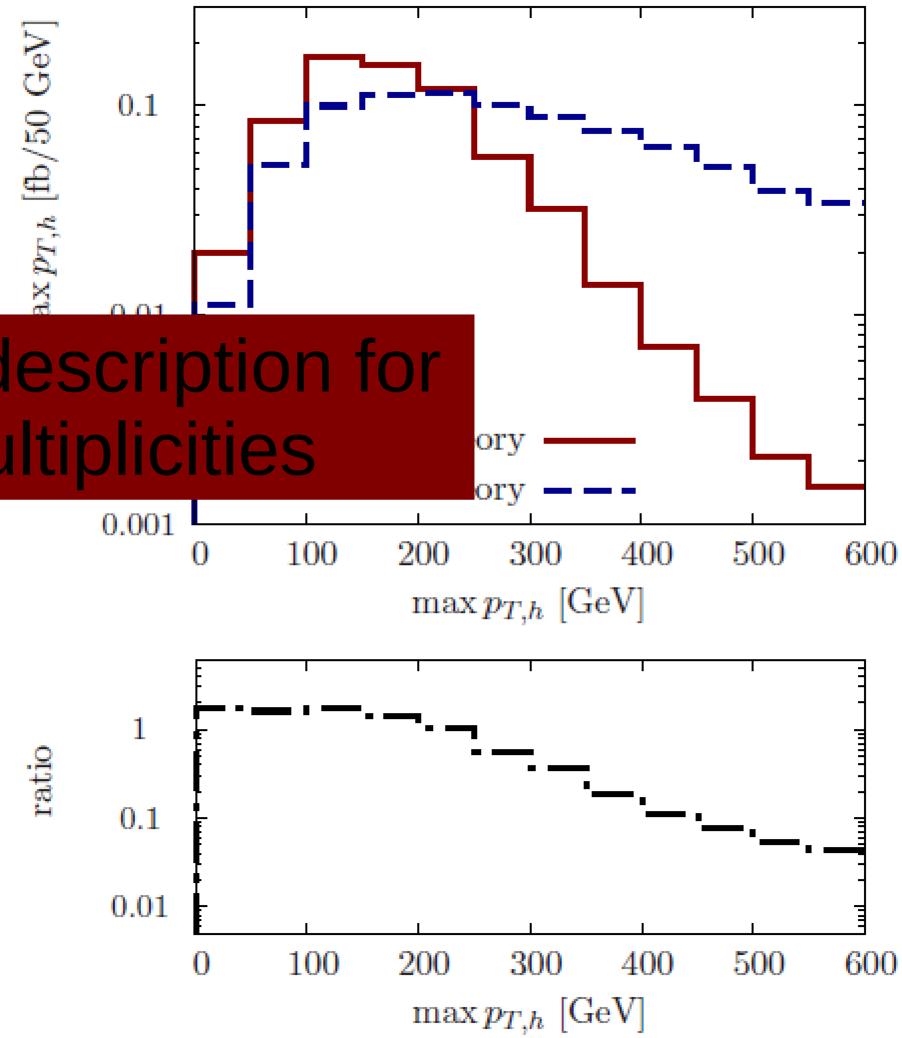

Equally bad description for higher multiplicities

Dolan et al. 1206.5001

Dolan et al. 1310.1084

Gluon fusion at NLO?

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K-factors for single Higgs: large
Expect similar behaviour from HH

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→ **Need for NLO results**

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➡ **Need for NLO results**

- What do we need to have the full NLO result?
  - Real emissions: HHj one loop (not easy but doable)
  - Virtual corrections: Including 2-loop amplitudes

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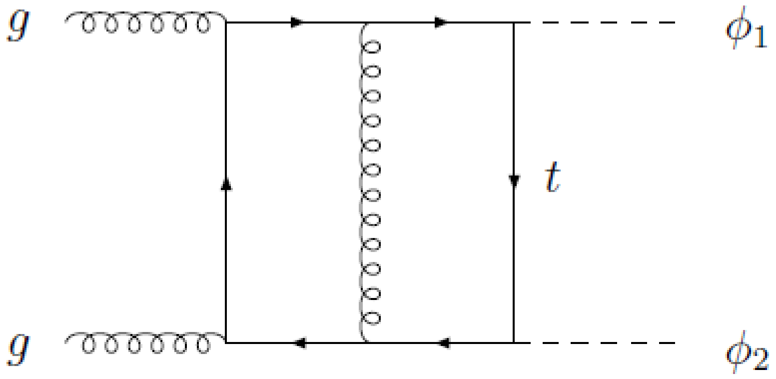

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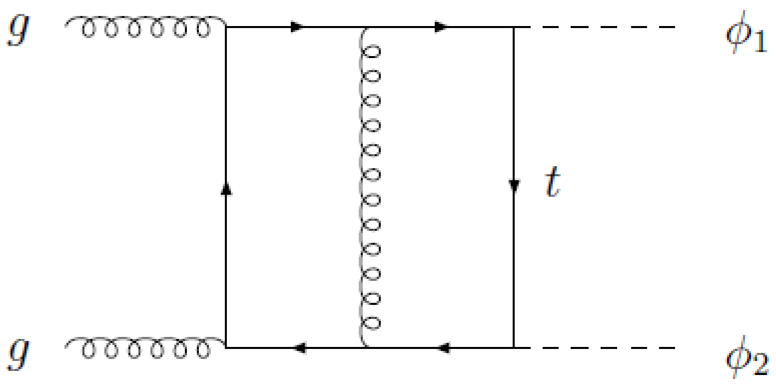
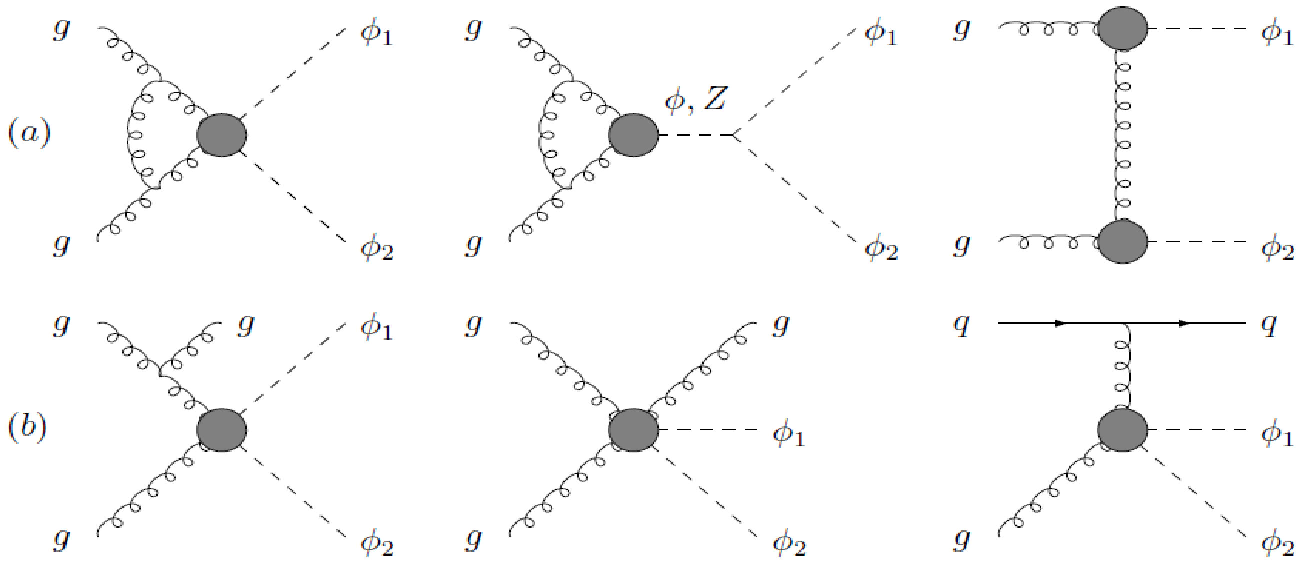


Beyond current loop technology

NLO corrections

- What did we have instead of the full NLO corrections?
- Corrections in the low energy theory:
  Dawson, Dittmaier, Spira hep-ph/9805244



- Given poor performance of the EFT at LO some improvement is needed

- Improved by using the full loop results for the Born cross section and available in Hpair code (total cross section)

Hpair approach

- Real and virtual corrections: factor out the Born cross-section (hep-ph/9805244)

Hpair approach

- Real and virtual corrections: factor out the Born cross-section (hep-ph/9805244)

$$\sigma_{\rm LO} \;=\; \int_{\tau_0}^{1} d\tau \, \frac{d\mathcal{L}^{gg}}{d\tau} \, \hat{\sigma}_{\rm LO}(Q^2 = \tau s)$$

$$\begin{aligned}
\Delta\sigma_{\rm virt} &= \frac{\alpha_s(\mu)}{\pi} \int_{\tau_0}^{1} d\tau \, \frac{d\mathcal{L}^{gg}}{d\tau} \, \hat{\sigma}_{\rm LO}(Q^2 = \tau s) \; C, \\
\Delta\sigma_{gg} &= \frac{\alpha_s(\mu)}{\pi} \int_{\tau_0}^{1} d\tau \, \frac{d\mathcal{L}^{gg}}{d\tau} \int_{\tau_0/\tau}^{1} \frac{dz}{z} \, \hat{\sigma}_{\rm LO}(Q^2 = z\tau s) \left\{ -z P_{gg}(z) \log \frac{M^2}{\tau s} \right. \\
&\qquad \left. - \frac{11}{2}(1-z)^3 + 6[1 + z^4 + (1-z)^4] \left(\frac{\log(1-z)}{1-z} \right)_+ \right\}
\end{aligned}$$

Hpair approach

- Real and virtual corrections: factor out the Born cross-section (hep-ph/9805244)

LO cross-section with full top-mass dependence

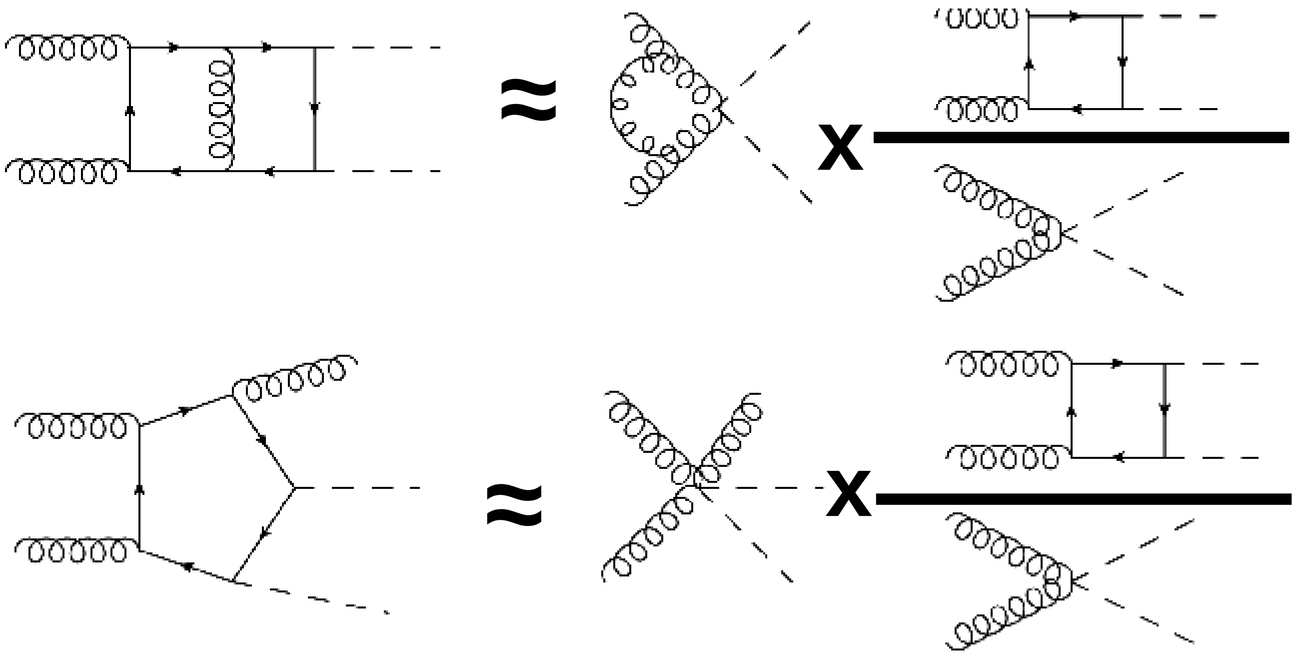
$$\sigma_{\rm LO} = \int_{\tau_0}^{1} d\tau \, \frac{d\mathcal{L}^{gg}}{d\tau} \, \hat{\sigma}_{\rm LO}(Q^2 = \tau s)$$

$$\Delta\sigma_{\rm virt} = \frac{\alpha_s(\mu)}{\pi} \int_{\tau_0}^{1} d\tau \, \frac{d\mathcal{L}^{gg}}{d\tau} \, \hat{\sigma}_{\rm LO}(Q^2 = \tau s) \, C,$$

$$\Delta\sigma_{gg} = \frac{\alpha_s(\mu)}{\pi} \int_{\tau_0}^{1} d\tau \, \frac{d\mathcal{L}^{gg}}{d\tau} \int_{\tau_0/\tau}^{1} \frac{dz}{z} \, \hat{\sigma}_{\rm LO}(Q^2 = z\tau s) \left\{ -zP_{gg}(z) \log \frac{M^2}{\tau s} - \frac{11}{2}(1-z)^3 + 6[1 + z^4 + (1-z)^4] \left(\frac{\log(1-z)}{1-z} \right)_+ \right\}$$

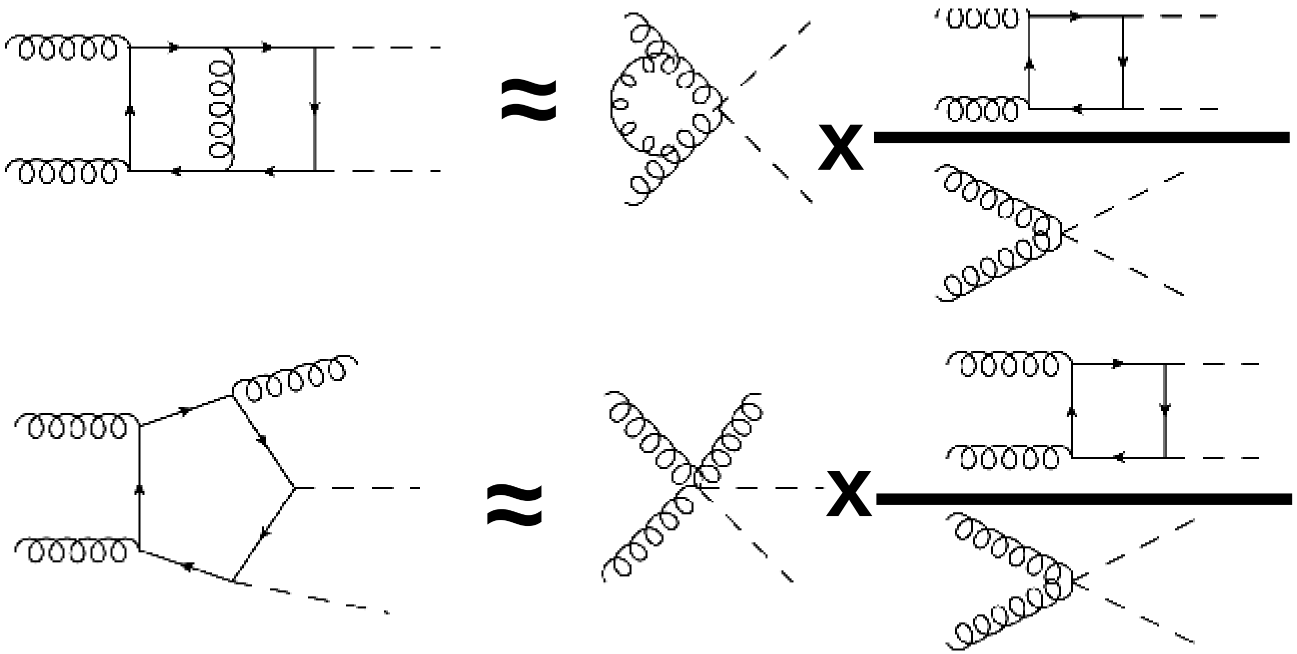
Hpair approach

- Real and virtual corrections: factor out the Born cross-section (hep-ph/9805244)



Hpair approach

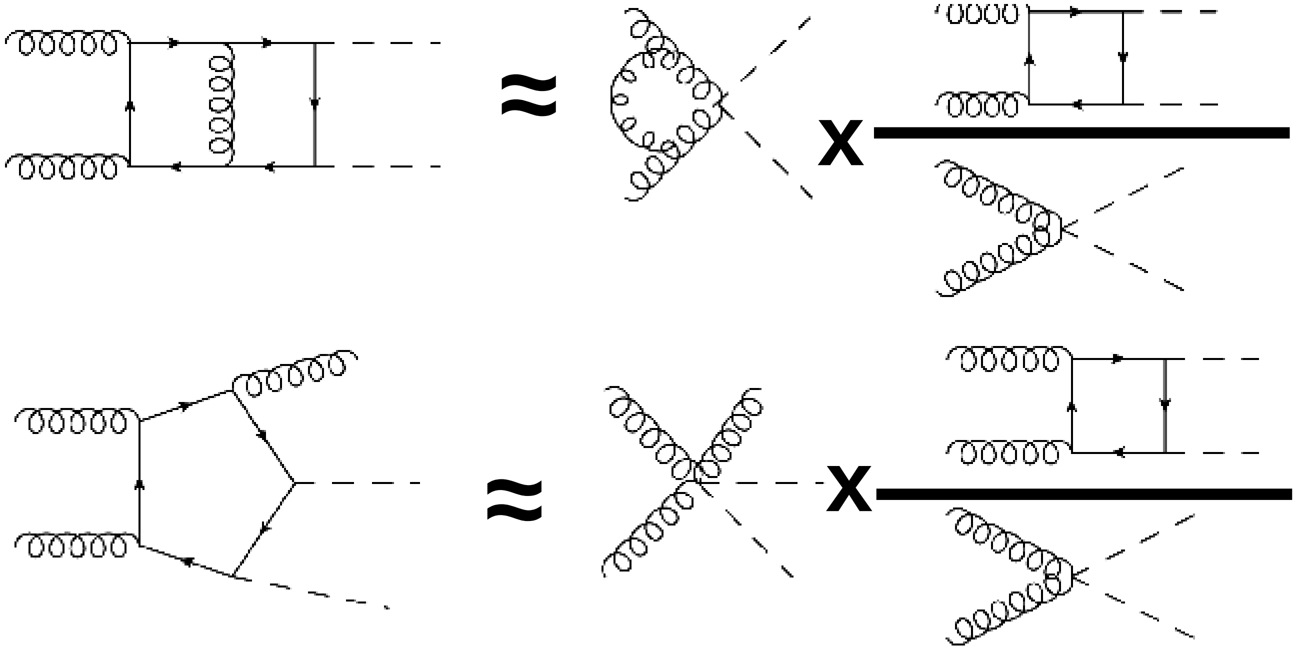
- Real and virtual corrections: factor out the Born cross-section (hep-ph/9805244)



But in fact the real emission amplitudes are calculable!

Hpair approach

- Real and virtual corrections: factor out the Born cross-section (hep-ph/9805244)



Approximation not necessary

But in fact the real emission amplitudes are calculable!

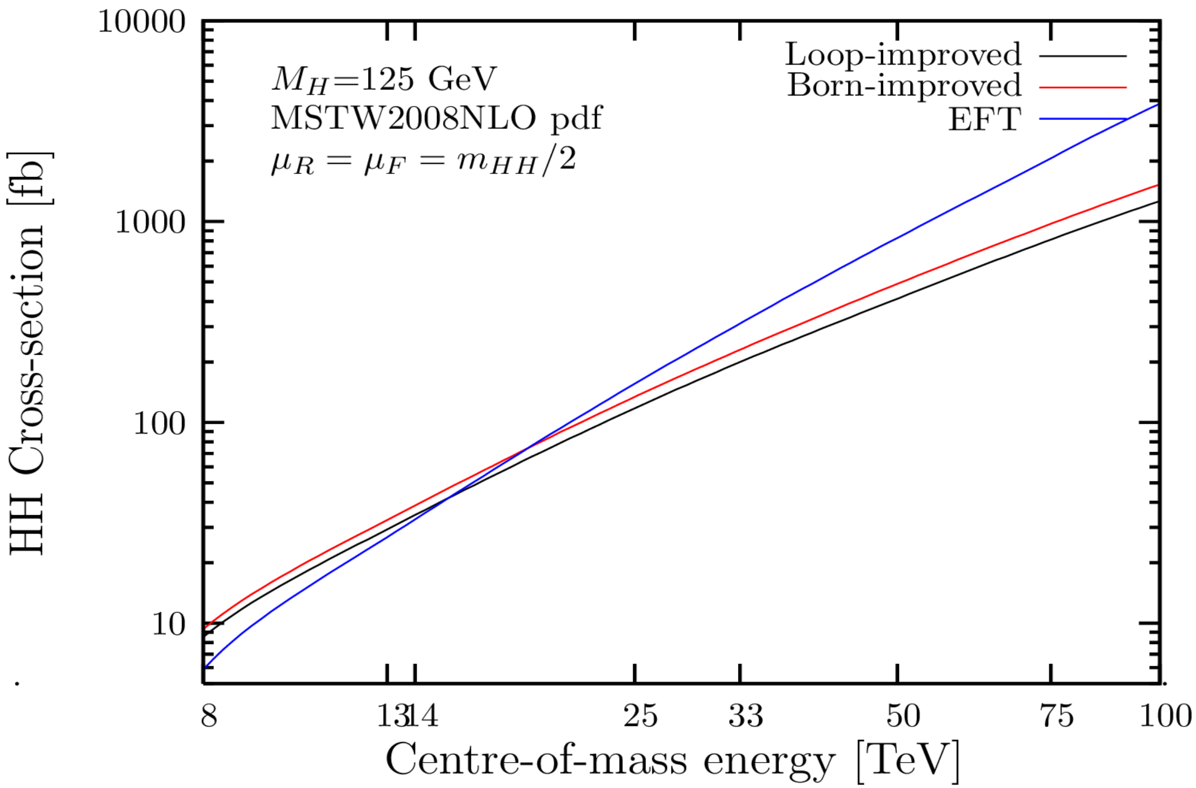
Room for improvement...

How did we improve this?

- What we have done:
  - Implementation of gluon fusion channel in aMC@NLO
  - Use LET to generate events at NLO
  - Reweigh on an event by event basis
  - For each event the relevant weights are modified using the results of loop matrix elements, obtained from MadLoop for both Born and real emission kinematics
- When done consistently improves previous results, because of better description of the real emission processes not included in previous results
- Calculation of the loop amplitudes performed with the complex mass scheme as implemented in MadLoop

Total cross-section results for gg

- Total cross section at a function of the CoM energy:
  - Loop-improved
  - Born-improved (similar to Hpair)
  - LET



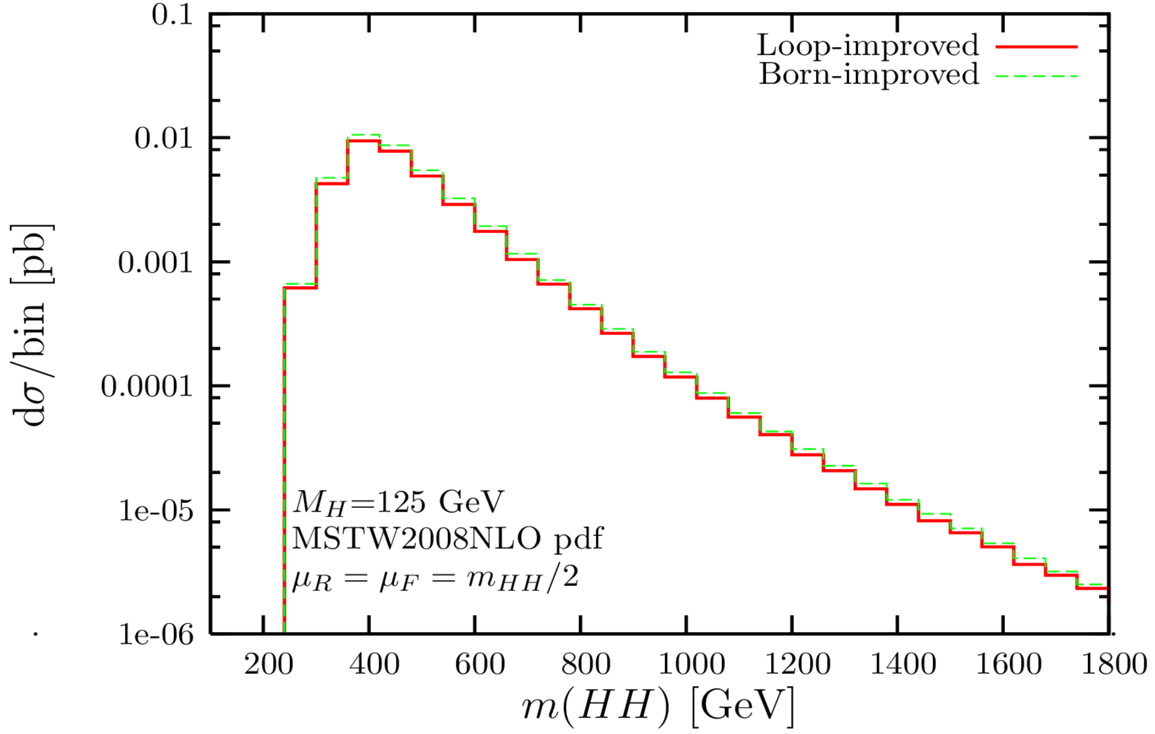
~10% difference between the loop improved (including real emission) and Born improved results

~3% effect of using the complex mass scheme

EFT quickly diverges at high energies

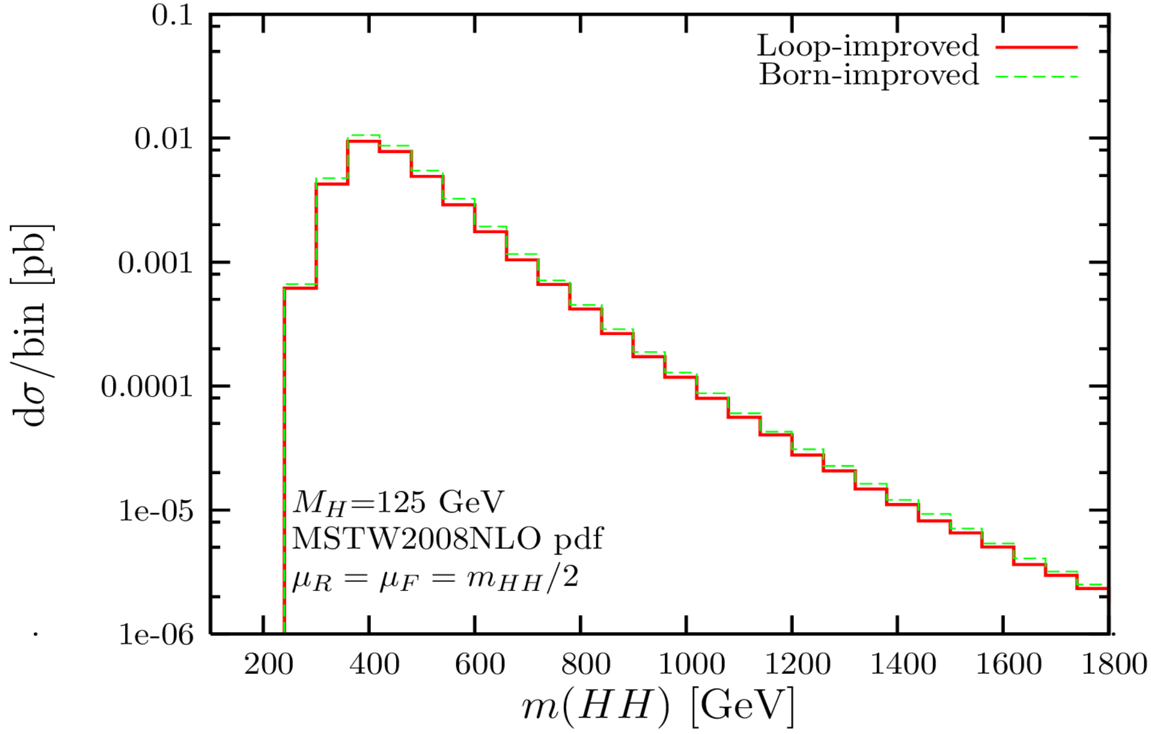
Differential distributions

Effect of using real emission amplitudes compared to simple Born reweighting



Differential distributions

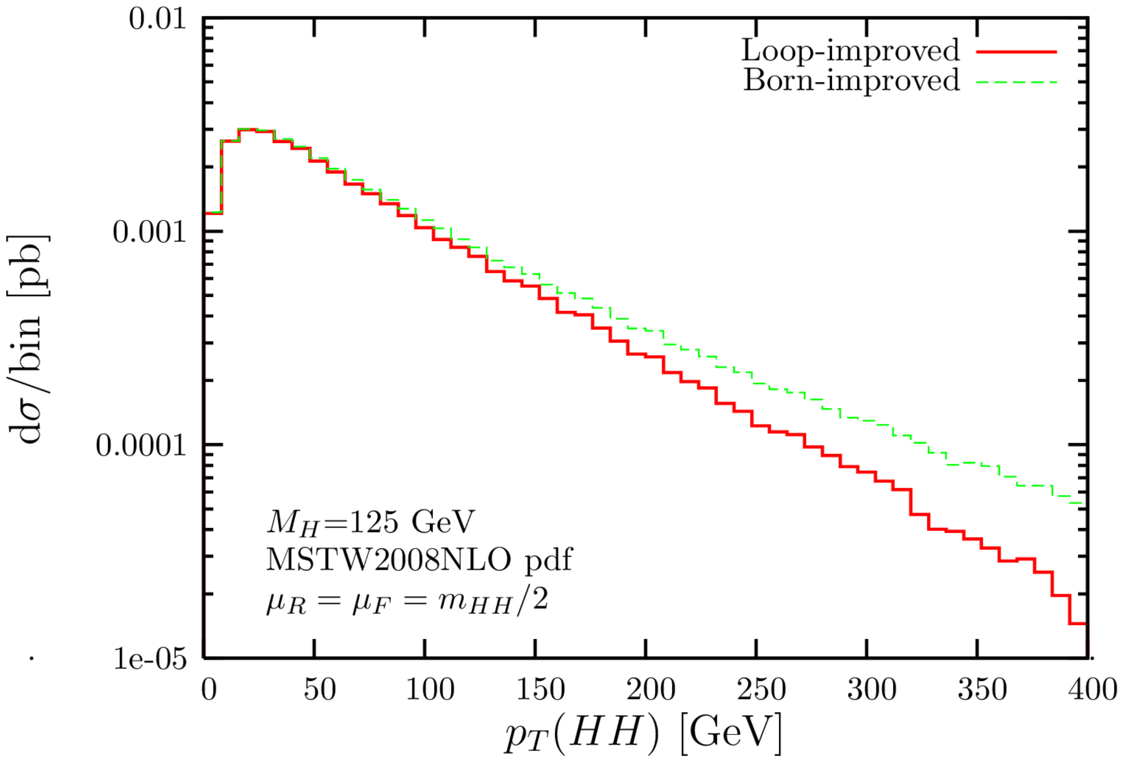
Effect of using real emission amplitudes compared to simple Born reweighting



No significant change in the shape for m(HH)

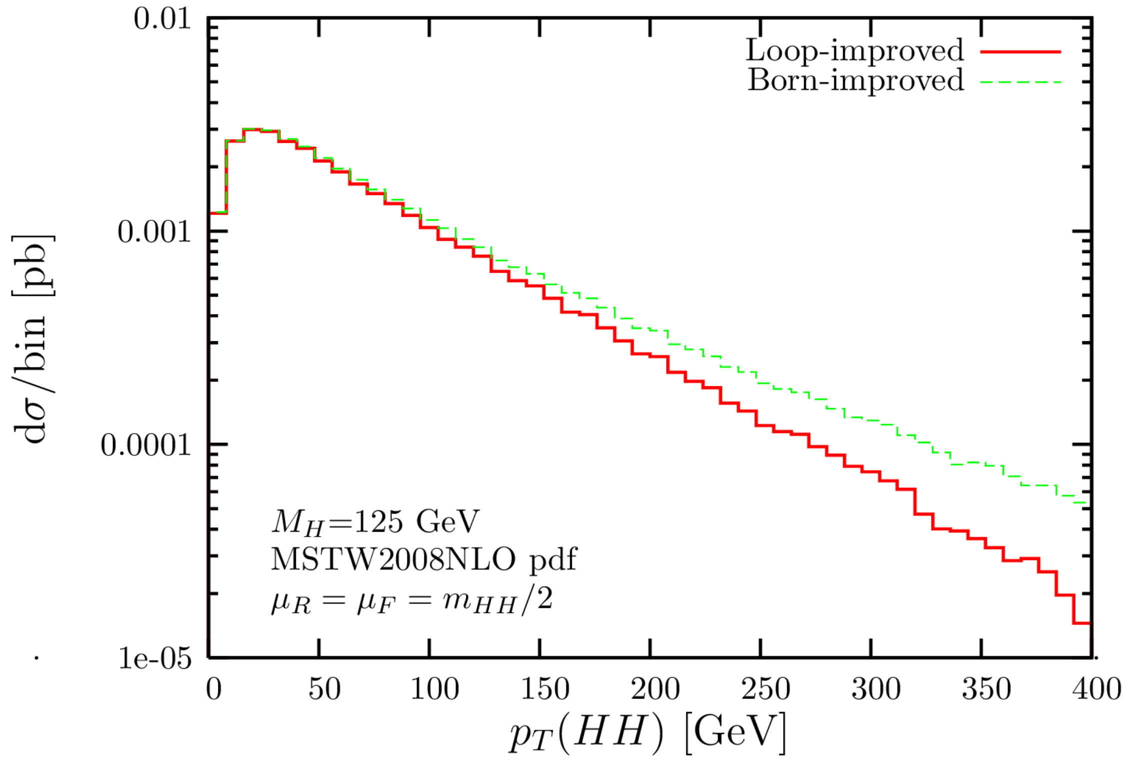
Differential distributions

Effect of using real emission amplitudes compared to simple Born reweighting



Differential distributions

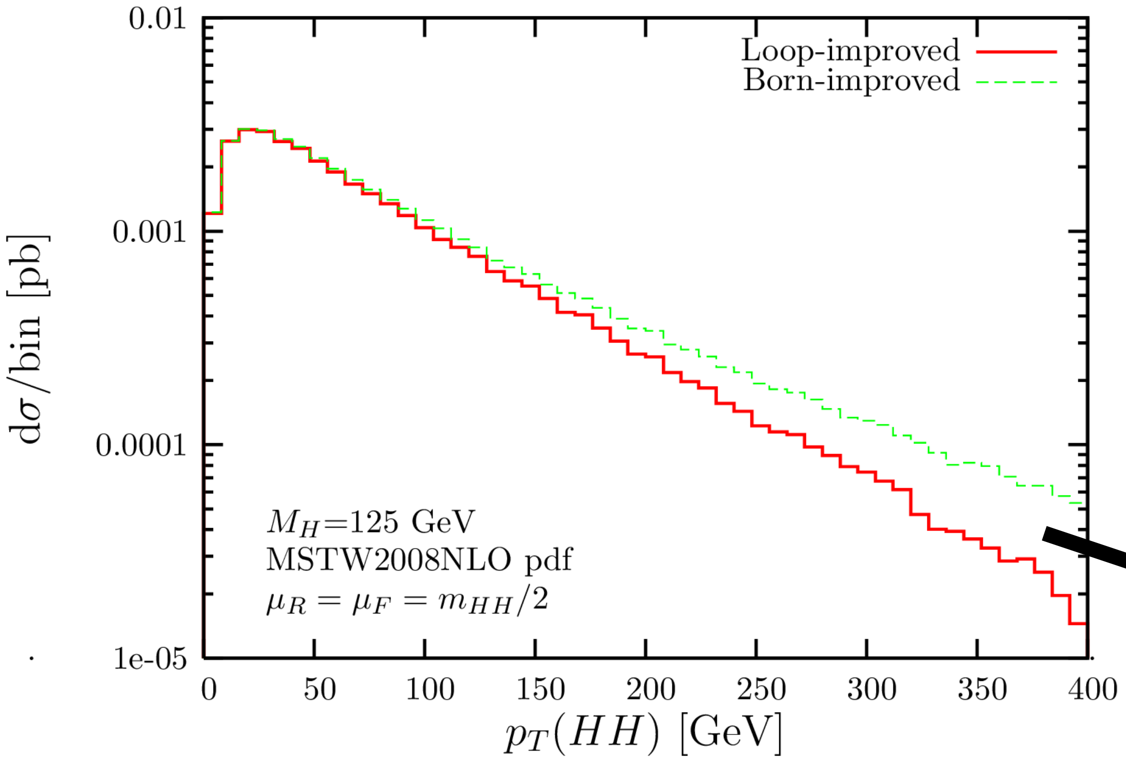
Effect of using real emission amplitudes compared to simple Born reweighting



Significant effect in the region of high pT(HH)

Differential distributions

Effect of using real emission amplitudes compared to simple Born reweighting



Significant effect in the region of high pT(HH)

Region dominated by real emission kinematics

Other results in gluon gluon fusion

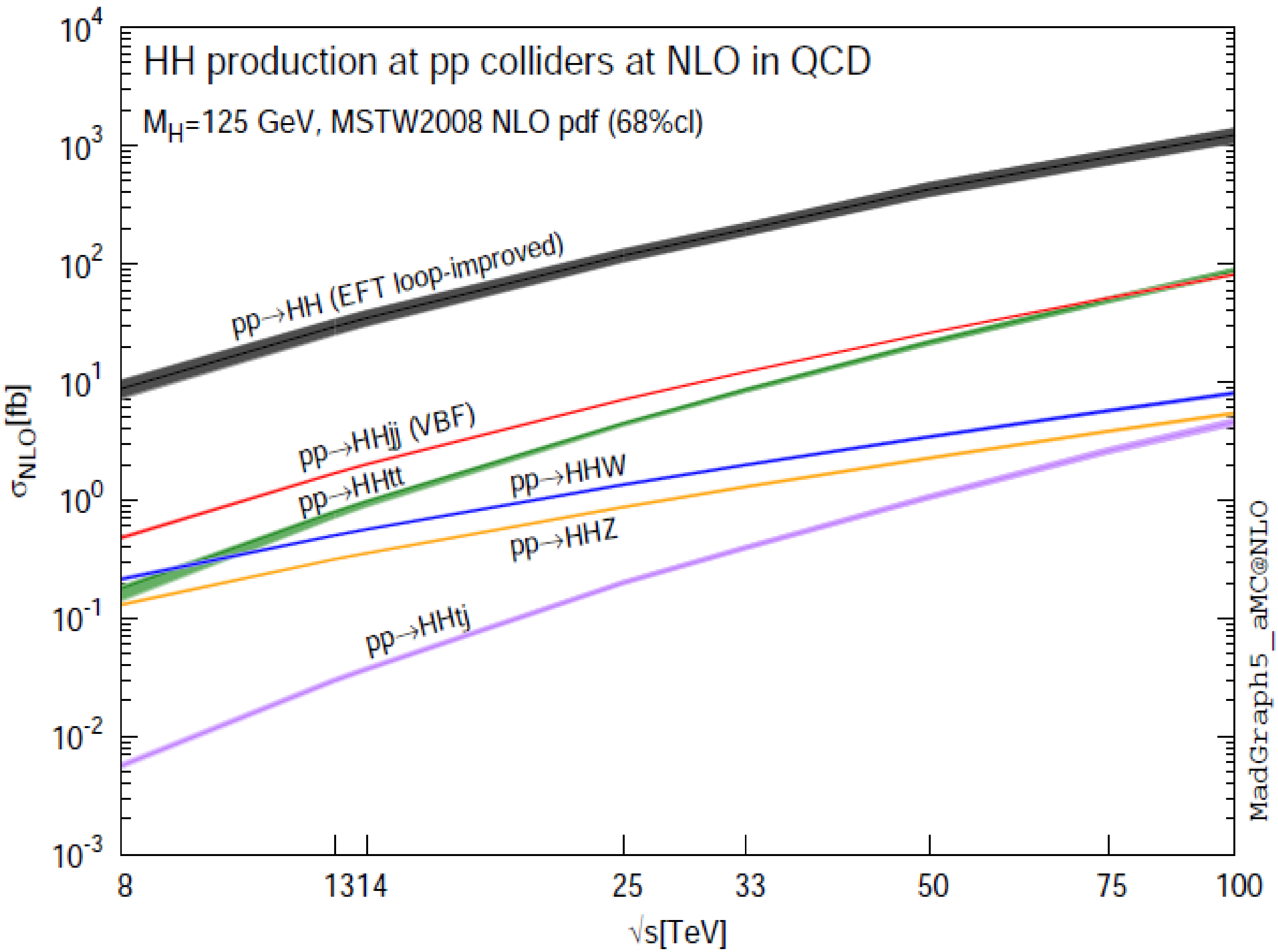
- Merged samples:
  - Li, Yan, Zhao arXiv:1312.3830
  - Maierhofer, Papaefstathiou arXiv:1401.0007
  - Exact one-loop born and real emission matrix elements but LO accuracy
- NNLO EFT corrected by full LO, De Florian and Mazzitelli, arxiv:1309.6594
  - Total cross section K-factor ~2.3 at 14TeV
- Expansion in $1/m_t$ at NLO, Grigo et al. arXiv:1305.7340
- Resummation: Shao et al. arXiv:1301.1245

Let's go back to the rest of the channels...

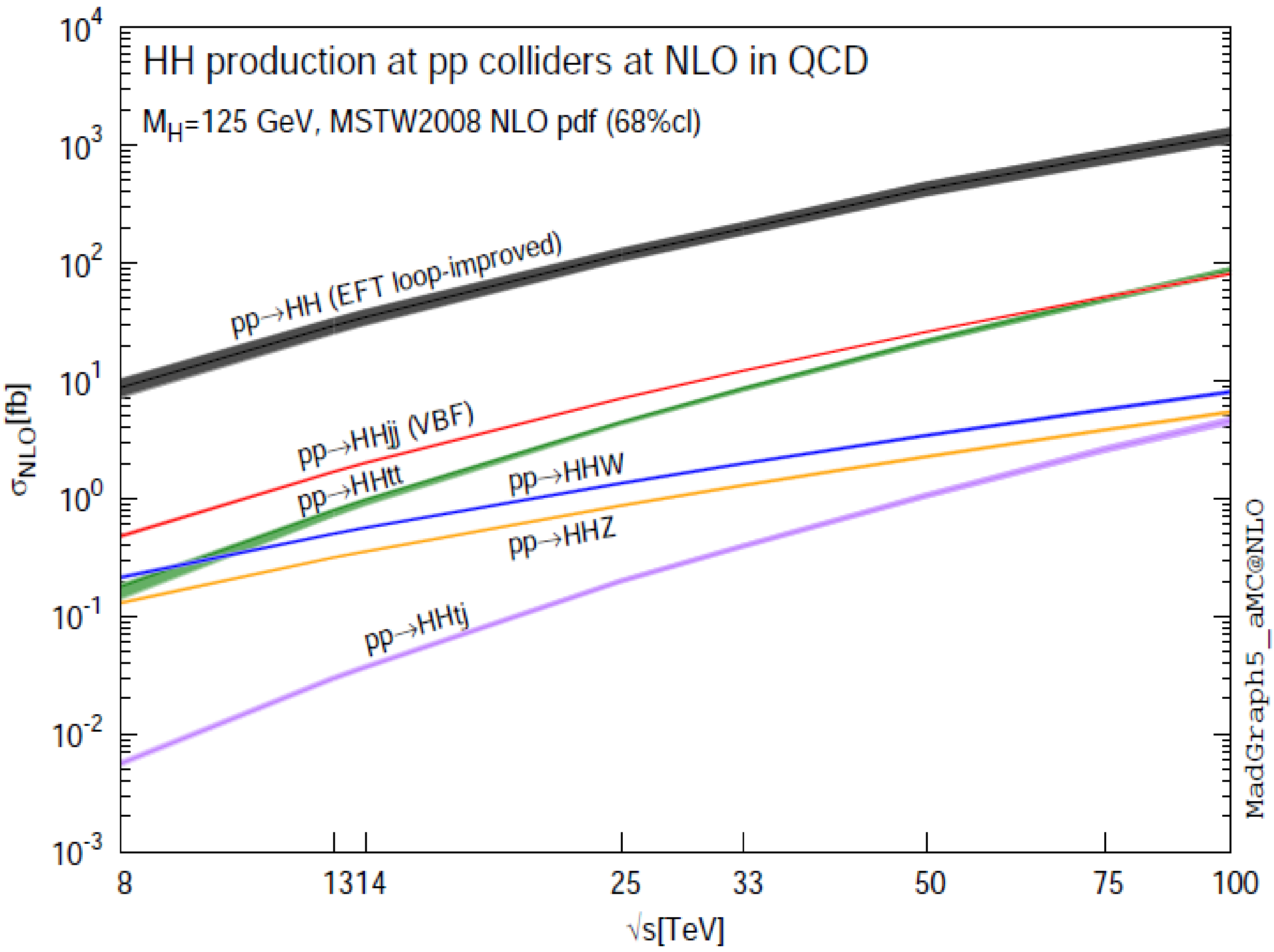
HH in other channels

- All other production channels start at tree level at LO: NLO results can be obtained automatically within aMC@NLO (1405.0301)
- Matched to parton showers with the MC@NLO method
- 'On the fly' calculation of scale and PDF uncertainties
- Fully differential results

aMC@NLO results: all channels

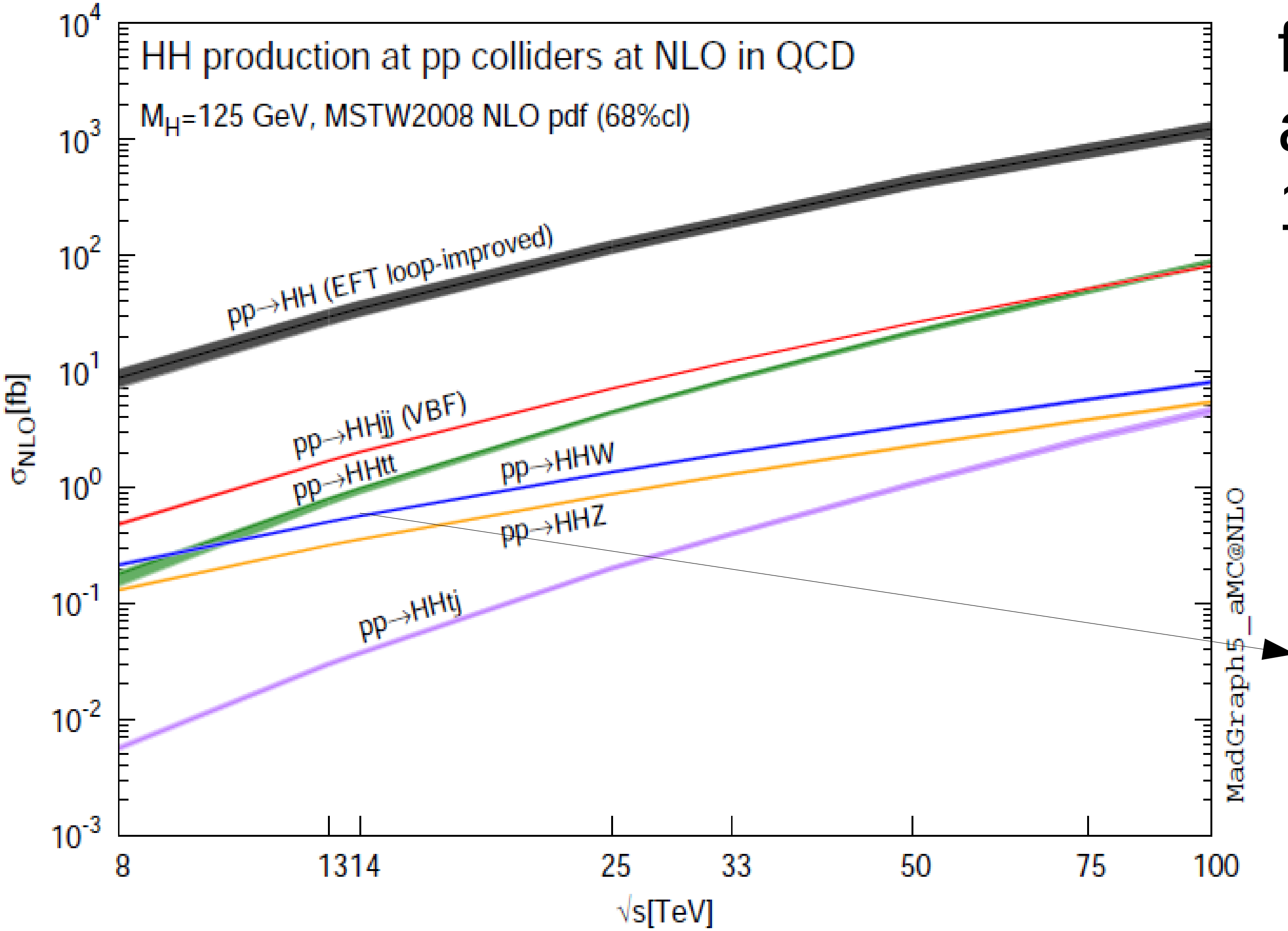


aMC@NLO results: all channels



Gluon gluon fusion dominates as ~35fb at 14TeV

aMC@NLO results: all channels



Gluon gluon fusion dominates as ~35fb at 14TeV

Small difference from single Higgs at 14 TeV:
Vector boson associated production and ttHH hierarchy reversed

Results

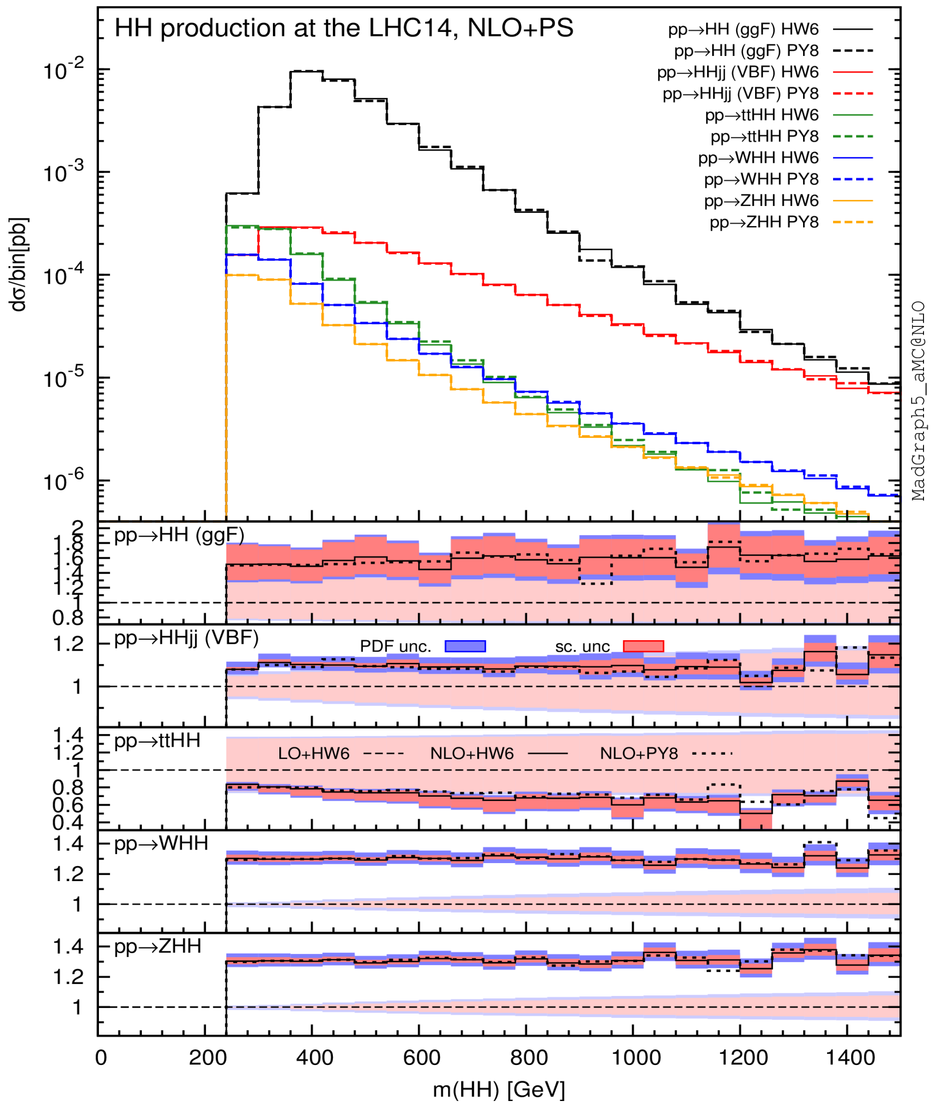
Total cross-section results

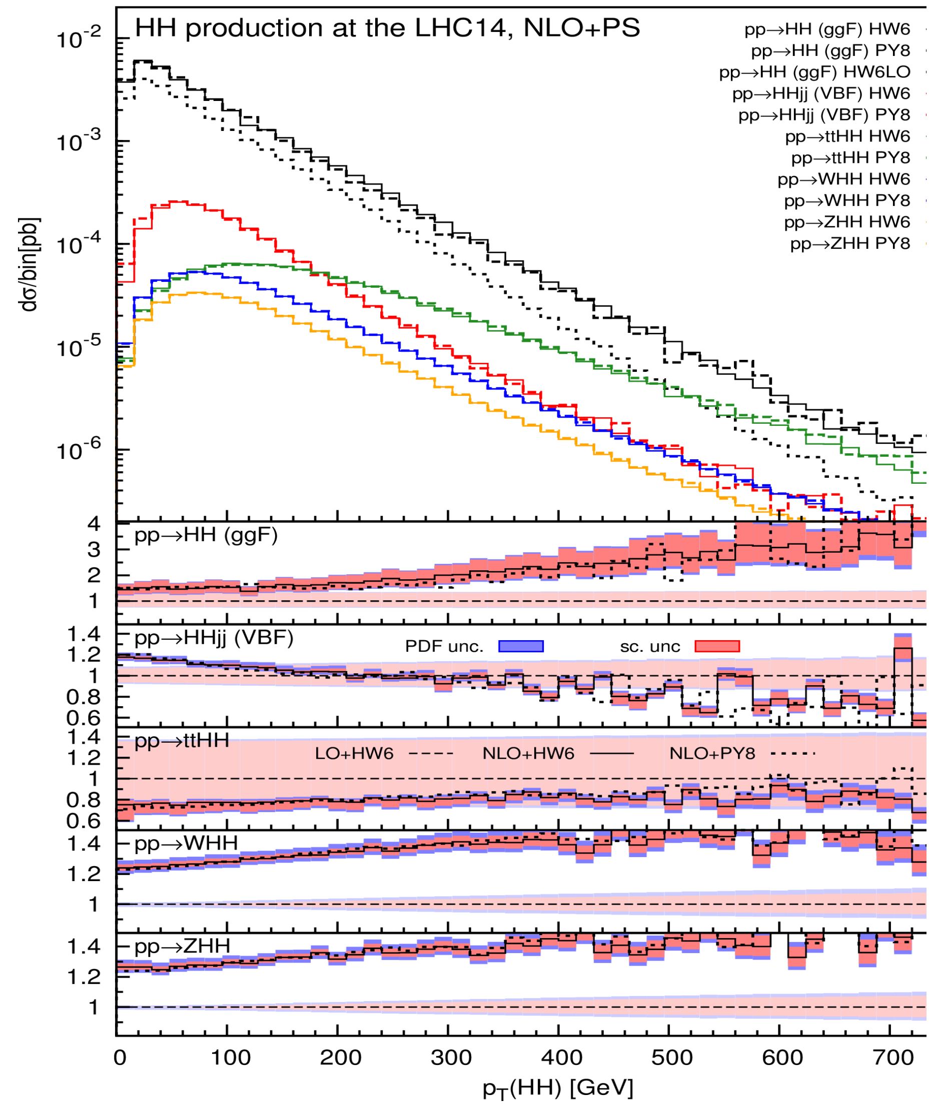
arxiv:1405.0301

	Process	Syntax	Cross section (pb)			
	Higgs pair production		LO 13 TeV		NLO 13 TeV	
h.1	$pp \to HH$ (Loop improved)	`p p > h h`	$1.772 \pm 0.006 \cdot 10^{-2}$	$^{+29.5\%}_{-21.4\%}$ $^{+2.1\%}_{-2.6\%}$	$2.763 \pm 0.008 \cdot 10^{-2}$	$^{+11.4\%}_{-11.8\%}$ $^{+2.1\%}_{-2.6\%}$
h.2	$pp \to HHjj$ (VBF)	`p p > h h j j $$ w+ w- z`	$6.503 \pm 0.019 \cdot 10^{-4}$	$^{+7.2\%}_{-6.4\%}$ $^{+2.3\%}_{-1.6\%}$	$6.820 \pm 0.026 \cdot 10^{-4}$	$^{+0.8\%}_{-1.0\%}$ $^{+2.4\%}_{-1.7\%}$
h.3	$pp \to HHW^{\pm}$	`p p > h h wpm`	$4.303 \pm 0.005 \cdot 10^{-4}$	$^{+0.9\%}_{-1.3\%}$ $^{+2.0\%}_{-1.5\%}$	$5.002 \pm 0.014 \cdot 10^{-4}$	$^{+1.5\%}_{-1.2\%}$ $^{+2.0\%}_{-1.6\%}$
h.4*	$pp \to HHW^{\pm}j$	`p p > h h wpm j`	$1.922 \pm 0.002 \cdot 10^{-4}$	$^{+14.2\%}_{-11.7\%}$ $^{+1.5\%}_{-1.1\%}$	$2.218 \pm 0.009 \cdot 10^{-4}$	$^{+2.7\%}_{-3.3\%}$ $^{+1.6\%}_{-1.1\%}$
h.5*	$pp \to HHW^{\pm}\gamma$	`p p > h h wpm a`	$1.952 \pm 0.004 \cdot 10^{-6}$	$^{+3.0\%}_{-3.0\%}$ $^{+2.2\%}_{-1.6\%}$	$2.347 \pm 0.007 \cdot 10^{-6}$	$^{+2.4\%}_{-2.0\%}$ $^{+2.1\%}_{-1.6\%}$
h.6	$pp \to HHZ$	`p p > h h z`	$2.701 \pm 0.007 \cdot 10^{-4}$	$^{+0.9\%}_{-1.3\%}$ $^{+2.0\%}_{-1.5\%}$	$3.130 \pm 0.008 \cdot 10^{-4}$	$^{+1.6\%}_{-1.2\%}$ $^{+2.0\%}_{-1.5\%}$
h.7*	$pp \to HHZj$	`p p > h h z j`	$1.211 \pm 0.001 \cdot 10^{-4}$	$^{+14.1\%}_{-11.7\%}$ $^{+1.4\%}_{-1.1\%}$	$1.394 \pm 0.006 \cdot 10^{-4}$	$^{+2.7\%}_{-3.2\%}$ $^{+1.5\%}_{-1.1\%}$
h.8*	$pp \to HHZ\gamma$	`p p > h h z a`	$1.397 \pm 0.003 \cdot 10^{-6}$	$^{+2.4\%}_{-2.5\%}$ $^{+2.2\%}_{-1.7\%}$	$1.604 \pm 0.005 \cdot 10^{-6}$	$^{+1.7\%}_{-1.4\%}$ $^{+2.3\%}_{-1.7\%}$
h.9*	$pp \to HHZZ$	`p p > h h z z`	$2.309 \pm 0.005 \cdot 10^{-6}$	$^{+3.9\%}_{-3.8\%}$ $^{+2.2\%}_{-1.7\%}$	$2.754 \pm 0.009 \cdot 10^{-6}$	$^{+2.3\%}_{-2.0\%}$ $^{+2.3\%}_{-1.7\%}$
h.10*	$pp \to HHZW^{\pm}$	`p p > h h z wpm`	$3.708 \pm 0.013 \cdot 10^{-6}$	$^{+4.8\%}_{-4.5\%}$ $^{+2.3\%}_{-1.7\%}$	$4.904 \pm 0.029 \cdot 10^{-6}$	$^{+3.7\%}_{-3.2\%}$ $^{+2.2\%}_{-1.6\%}$
h.11*	$pp \to HHW^{+}W^{-}$ (4f)	`p p > h h w+ w-`	$7.524 \pm 0.070 \cdot 10^{-6}$	$^{+3.5\%}_{-3.4\%}$ $^{+2.3\%}_{-1.7\%}$	$9.268 \pm 0.030 \cdot 10^{-6}$	$^{+2.3\%}_{-2.1\%}$ $^{+2.3\%}_{-1.7\%}$
h.12	$pp \to HHt\bar{t}$	`p p > h h t t~`	$6.756 \pm 0.007 \cdot 10^{-4}$	$^{+30.2\%}_{-21.6\%}$ $^{+1.8\%}_{-1.8\%}$	$7.301 \pm 0.024 \cdot 10^{-4}$	$^{+1.4\%}_{-5.7\%}$ $^{+2.2\%}_{-2.3\%}$
h.13	$pp \to HHtj$	`p p > h h tt j`	$1.844 \pm 0.008 \cdot 10^{-5}$	$^{+0.0\%}_{-0.6\%}$ $^{+1.8\%}_{-1.8\%}$	$2.444 \pm 0.009 \cdot 10^{-5}$	$^{+4.5\%}_{-3.1\%}$ $^{+2.8\%}_{-3.0\%}$
h.14*	$pp \to HHb\bar{b}$	`p p > h h b b~`	$7.849 \pm 0.022 \cdot 10^{-8}$	$^{+34.3\%}_{-23.9\%}$ $^{+3.1\%}_{-3.7\%}$	$1.084 \pm 0.012 \cdot 10^{-7}$	$^{+7.4\%}_{-10.8\%}$ $^{+3.1\%}_{-3.7\%}$

Significant decrease of scale and PDF uncertainties for the NLO results
Gluon gluon fusion dominating by an order of magnitude over the other channels

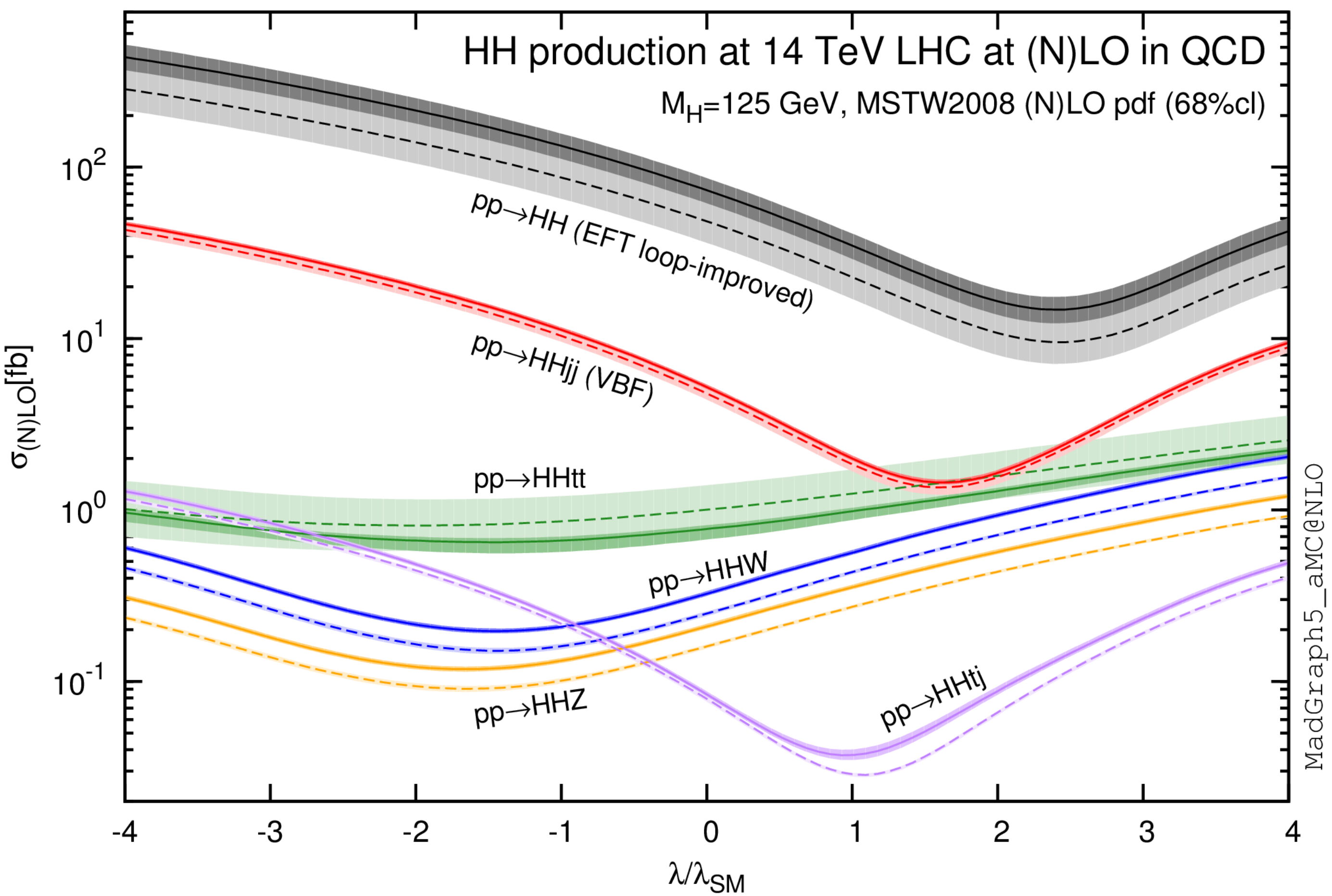
Differential distributions





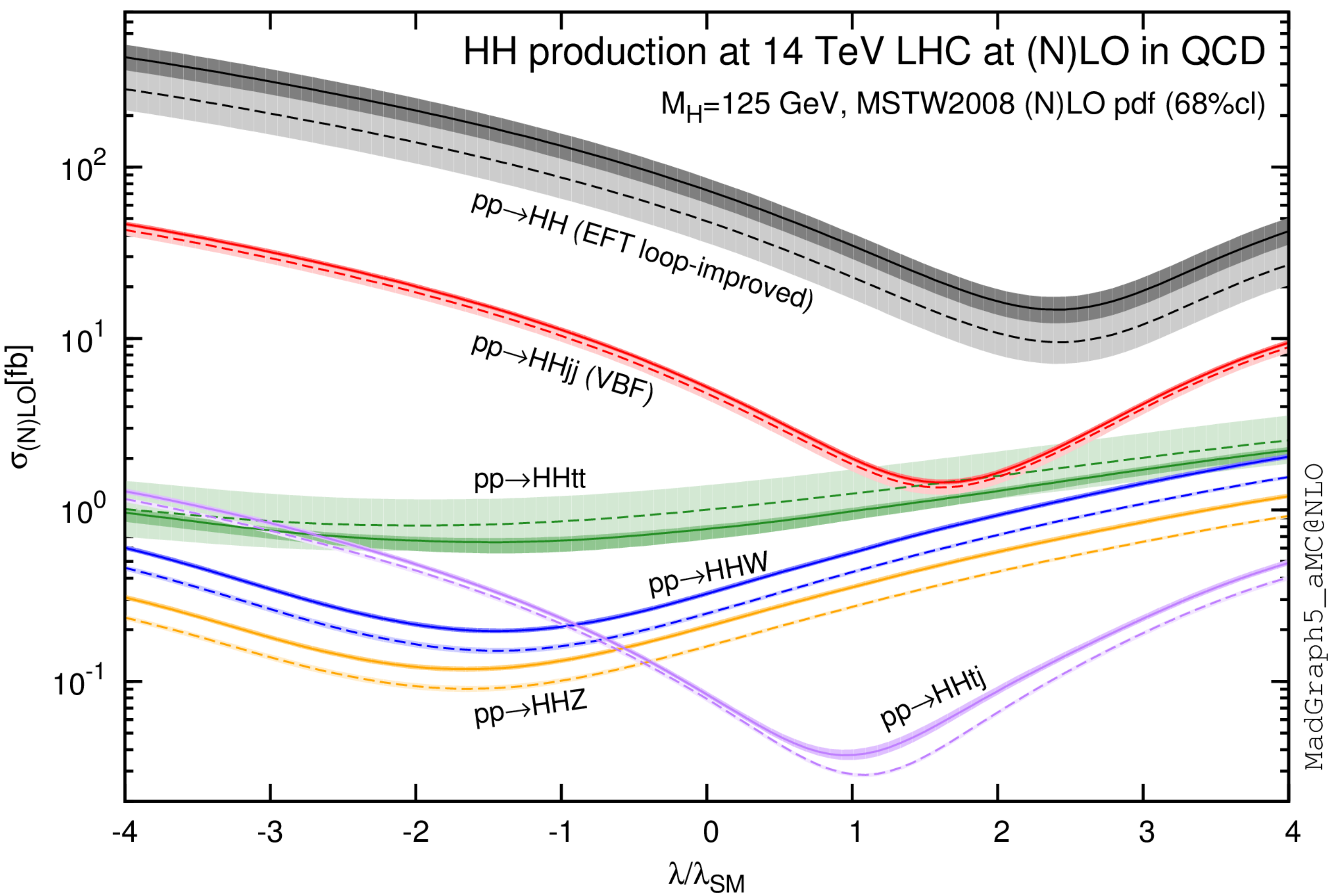
Including NLO and PS effects: best available predictions

Dependence on the trilinear Higgs coupling



Sensitivity of different channels to λ

Dependence on the trilinear Higgs coupling



Sensitivity of different channels to λ

Significant reduction of the scale uncertainty at NLO, especially for gg and ttHH

Calculation codes

- Gluon-gluon fusion
- LO
  - MadGraph 5
    - Exact LO matrix elements for pair production
    - Codes can be downloaded from:
      - https://cp3.irmp.ucl.ac.be/projects/madgraph/wiki/HiggsPairProduction
- NLO
  - Special code developed (slow because of loop calculation but optimised to run on a cluster)
- All other channels
  - Out of the box with aMC@NLO

Phenomenological studies

We have the results... Now what?

- Theory predictions: NLO expect ~30-40fb at 14TeV
- Can we actually see this process at the LHC?
- All results shown before obtained with no H decays
- Which are the promising decay channels to constrain the trilinear Higgs coupling?

$bb\gamma\gamma$ (1212.5581)
$bb\tau\tau$ (1206.5001, 1212.5581)
bbWW (1209.1489, 1212.5581)
bbbb (1404.7139)

Always a compromise between huge backgrounds and tiny cross sections...

Phenomenological studies

- Great boost from boosted techniques for previously impossible channels such as bbbb-BDRS
- Combining several channels leads to ~30% constraint estimate for the SM value at the high luminosity LHC

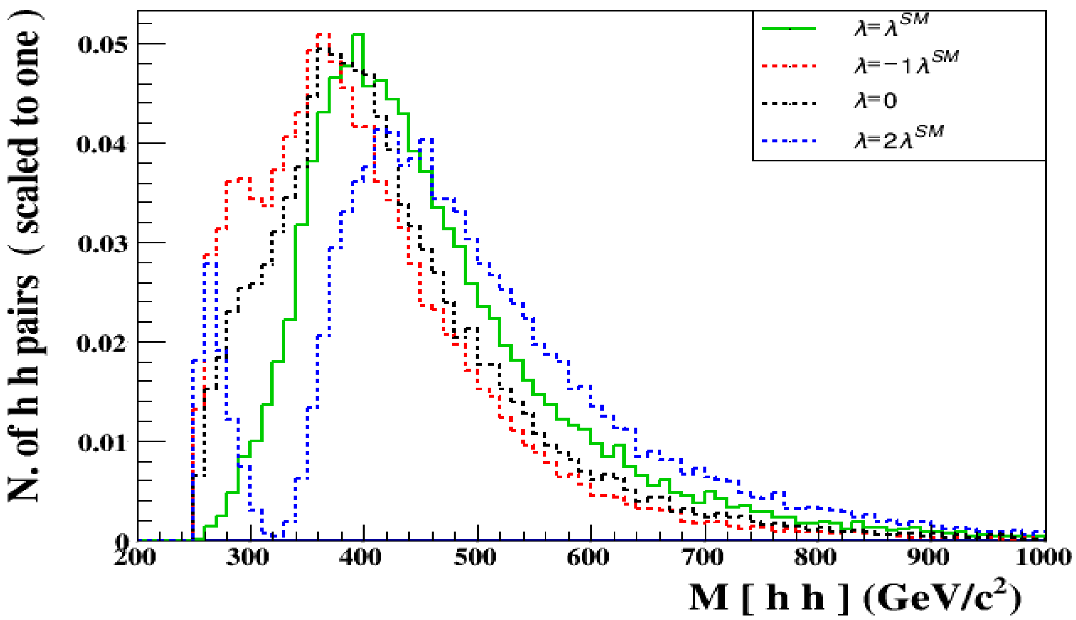
process	constraint ($\times\lambda_{\mathrm{SM}}$)
$hh \to (b\bar{b})(\tau^+\tau^-)$	$\lambda = 1.00^{+0.40}_{-0.31}$
$hh \to (b\bar{b})(\gamma\gamma)$	$\lambda = 1.00^{+0.87}_{-0.52}$
$hh \to (b\bar{b})(W^+W^-)$	$\lambda = 1.00^{+0.46}_{-0.35}$
combination	$\lambda = 1.00^{+0.35}_{-0.23}$

Table from 1404.7139 3000fb^{-1} at 14 TeV

Most studies performed using LO implementations of HH production (using EFT k-factors)
Interesting to see how things change using NLO predictions

BSM physics in HH

- BSM trilinear coupling (arxiv:1206.5001,1210.8166,1311.2931)

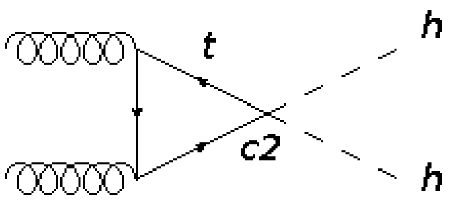


Normalised plots 14TeV

Shape depends on the value of the trilinear Higgs coupling because of interference between the diagrams

BSM physics in HH

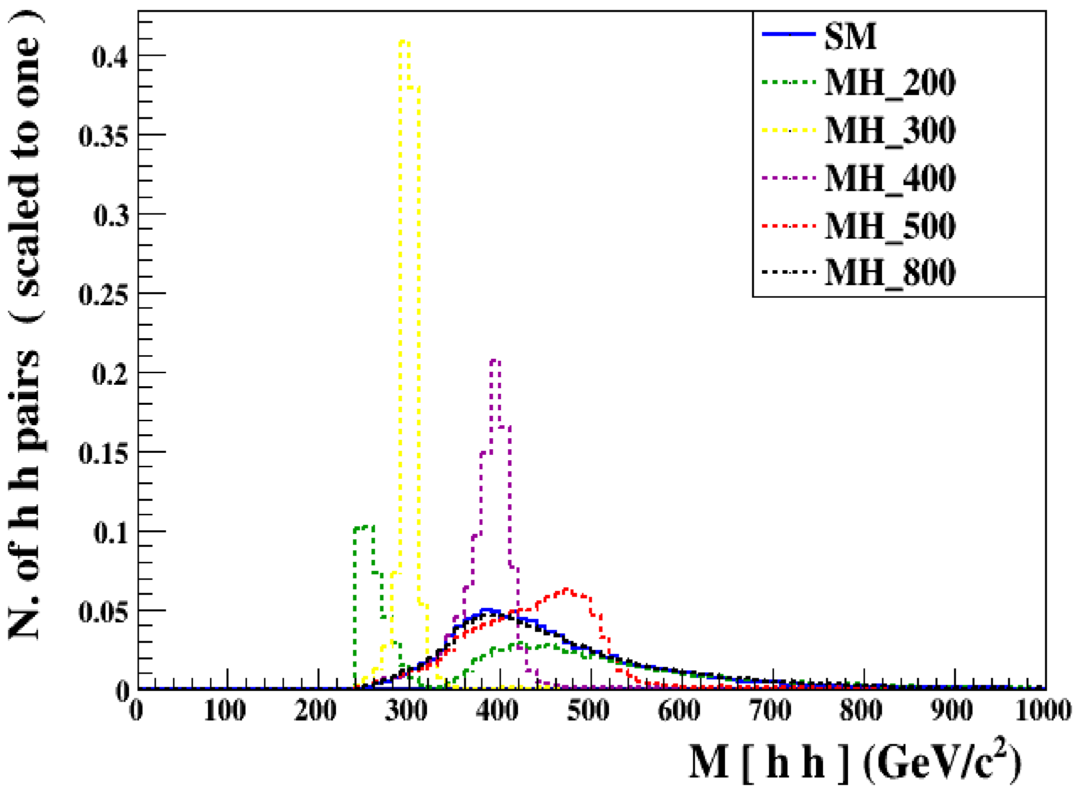
- Other BSM contributions?
- Non SM Yukawa couplings (1205.5444, 1206.6663)
- ttHH interactions (1205.5444)

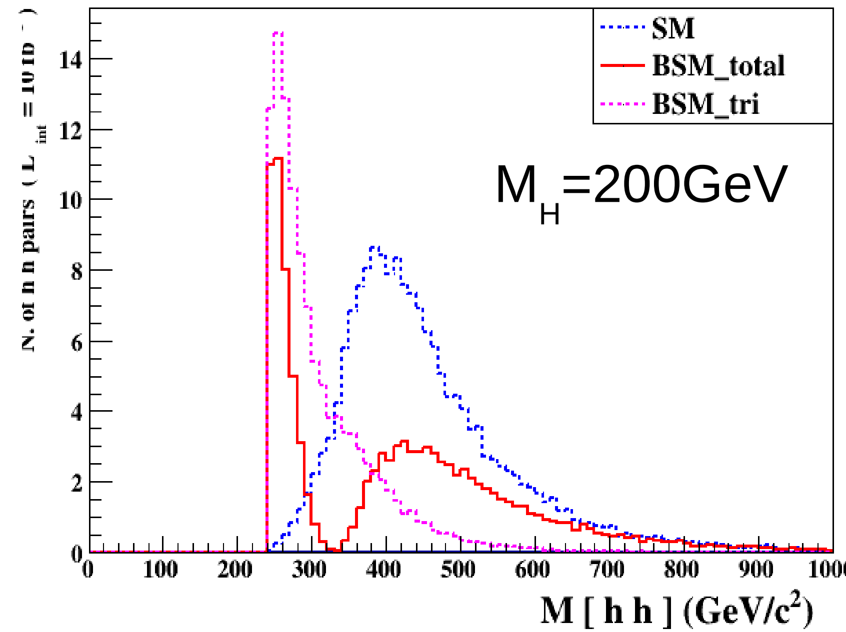


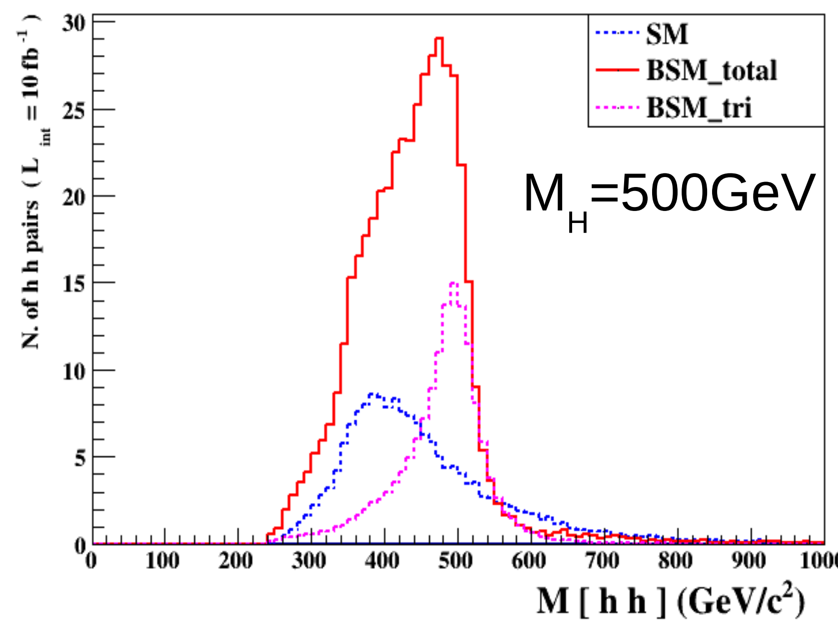
- Resonances from extra dimensions (1303.6636)
- Vector-like quarks (1009.4670, 1206.6663)
- 2HDM (1009.4670, 1210.8166, 1403.1264)
- Light coloured scalars (1207.4496)

RICH PHENOMENOLOGY

Example:additional scalar with SM couplings
Toy model







Interference changing sign for different masses

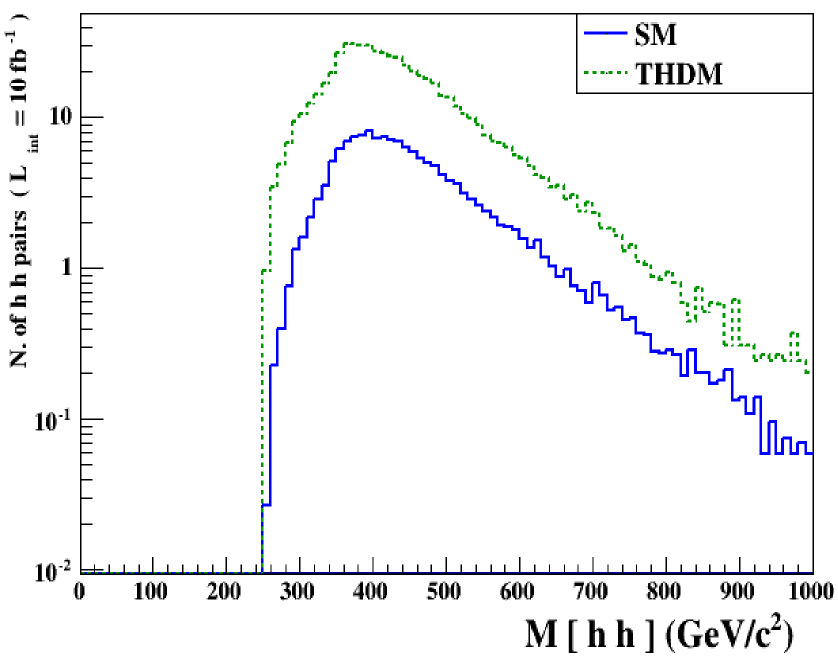
Higgs pair production in the 2HDM

- 2HDM
  - Scalar: Light Higgs, h1
    Heavy Higgs, h2
  - Pseudoscalar, h3
  - Charged Higgses, h+, h-
- Light Higgs pair production discussed in arxiv:1403.1264
- Benchmark points not excluded by LHC data studied: can lead to an enhancement of up to a factor of 60 in the cross section

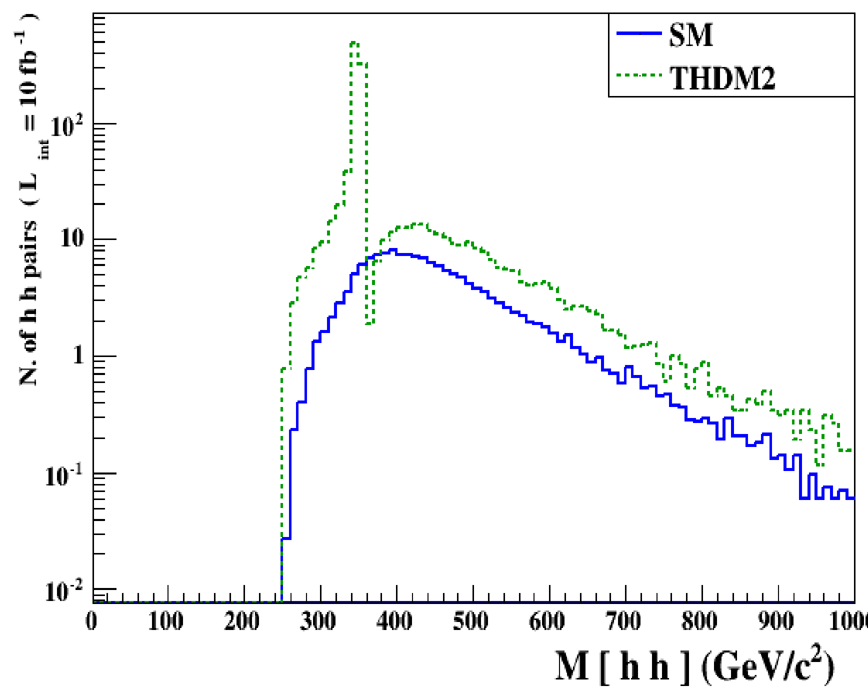
2HDM examples

- Results for two 2HDM benchmark points (provided by David Lopez Val)

M_H=350GeV



sin(b-a)=0.8



sin(b-a)=0.95

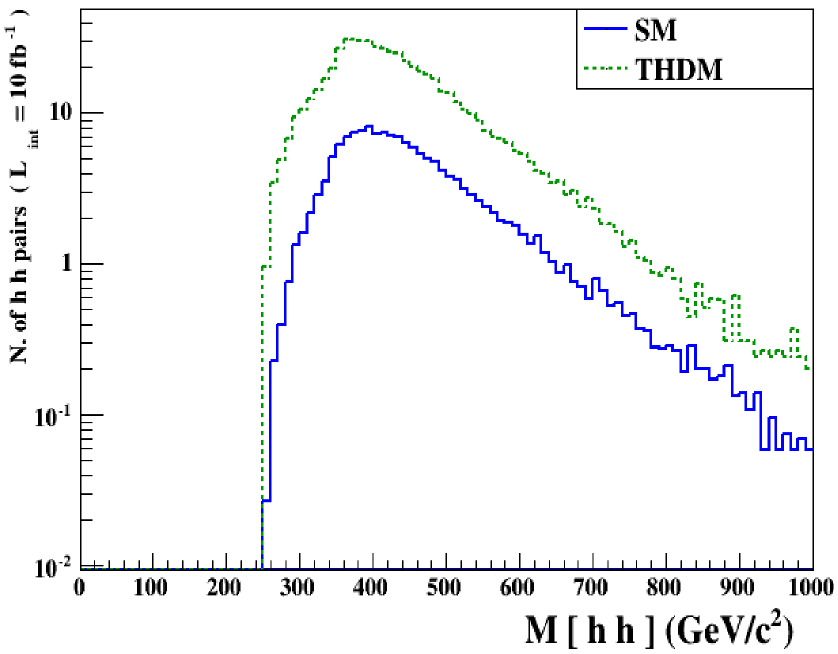
LO results with MadGraph 5

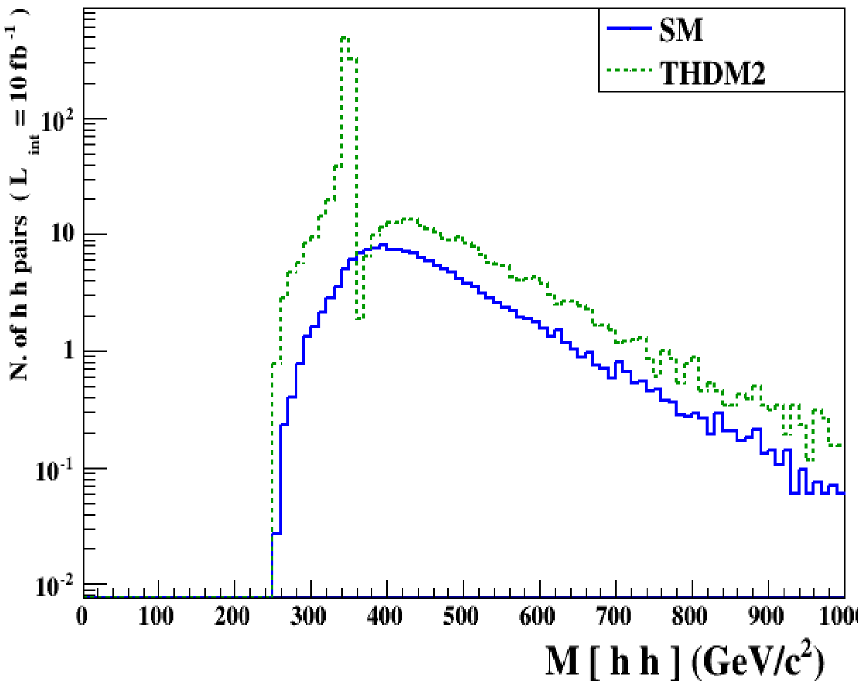
2HDM examples

- Results for two 2HDM benchmark points (provided by David Lopez Val)

Results strongly depend on the modification of the light Higgs couplings and the suppression of heavy Higgs couplings

M_H=350GeV



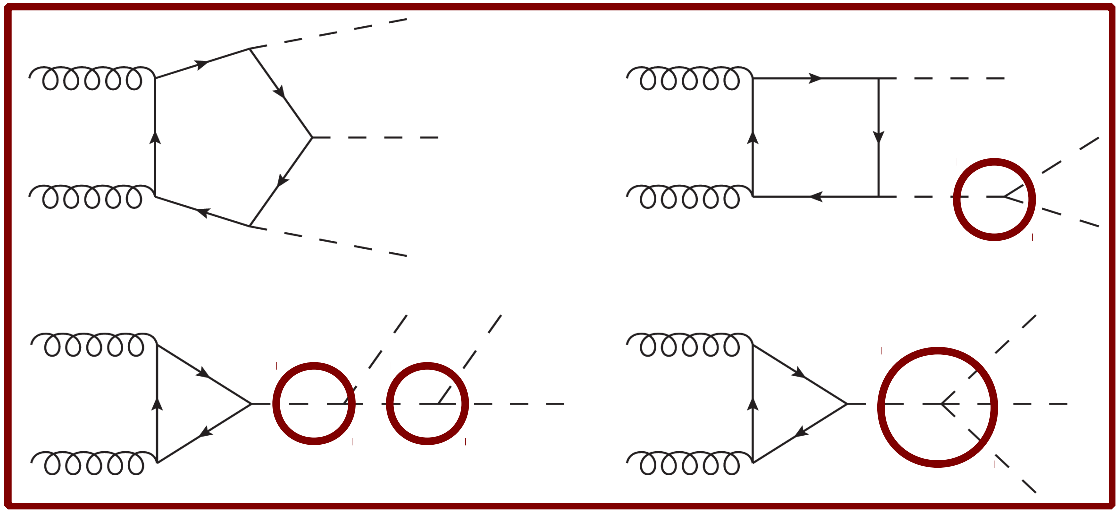


sin(b-a)=0.8

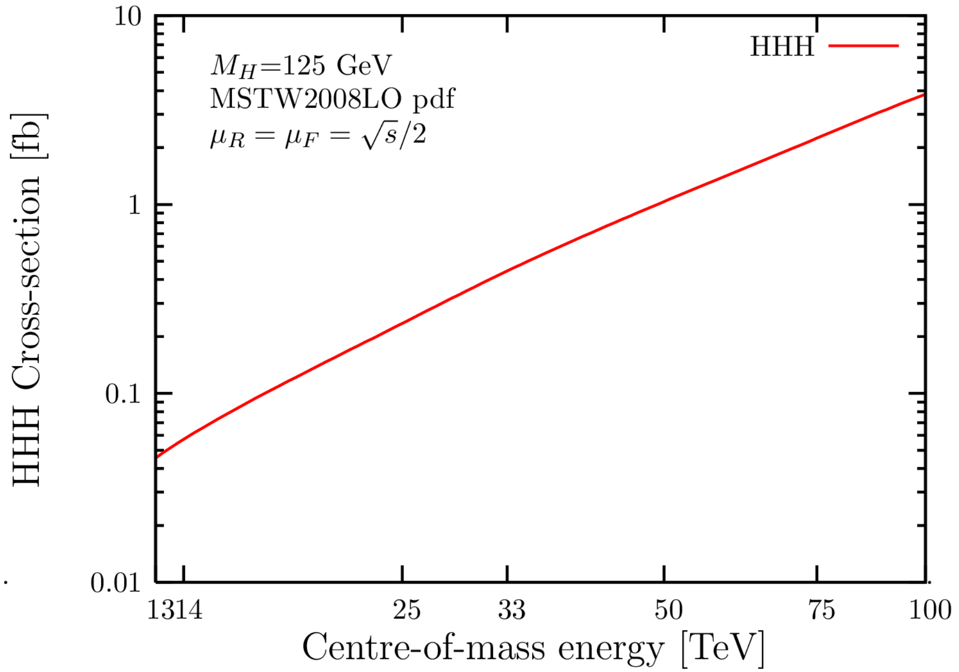
LO results with MadGraph 5

sin(b-a)=0.95

Triple Higgs production?



Access to both the trilinear and quartic couplings



Extremely challenging even for the 100TeV collider

Conclusions and Outlook

- Higgs pair production key to the measurement of triple Higgs coupling
- Gluon-gluon fusion is the dominant production channel for which we now have an improved theoretical prediction
- Presented results of an efficient MC implementation of the process at NLO provided in an automated way by aMC@NLO
- Results can now be used for phenomenological studies

Conclusions and Outlook

- Studies including various decay channels suggest sensitivity to the trilinear Higgs coupling for the high luminosity LHC
- Higgs pair production is a very interesting process in the search for new physics, wide range of BSM models can be investigated
- Most obvious next step: 2HDM treatment at NLO, aim to study non excluded benchmark points in detail

Thanks for your attention...